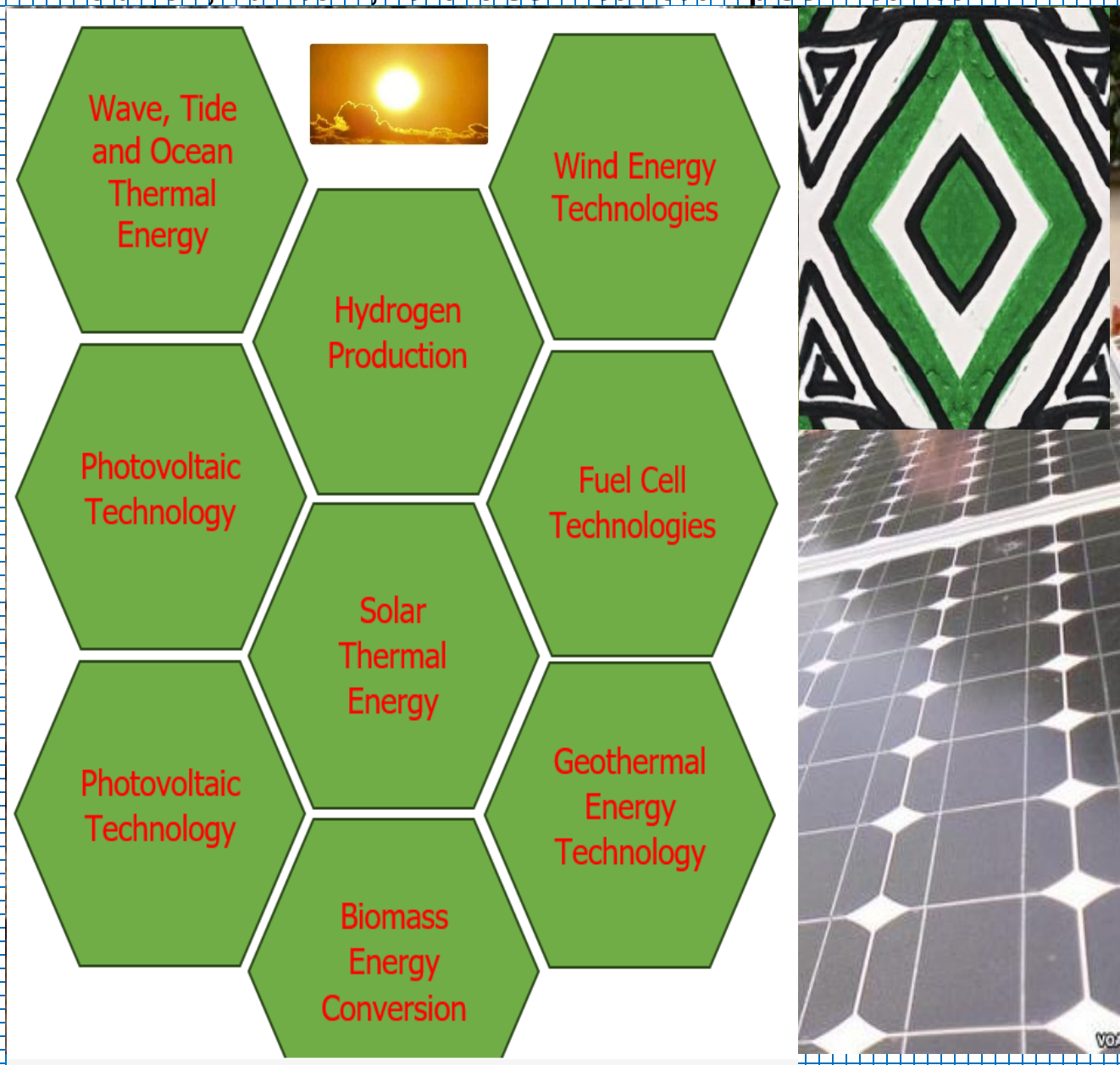




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The Nigerian Journal of Renewable Energy Research (NJRER) is a Peer-reviewed, Open Access journal that publishes papers relating to the science and technology of energy generation, distribution, storage, and management. It also publishes studies into the environmental, societal, and economic impacts of renewable energy use and policy.

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“Technology has given us this wonderful opportunity to have low energy costs. We have to seize that, rather than keep debating and discussing and fighting over it.”

Michael Porter

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COMPREHENSIVE PLANNING AND REGULATORY FRAMEWORK FOR LARGE-SCALE GROUND-MOUNTED SOLAR PHOTOVOLTAIC DEVELOPMENT IN NIGERIA

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ABSTRACT

The rapid growth of solar photovoltaic (PV) deployment globally has increased interest in ground-mounted solar farms as a strategic solution for enhancing renewable electricity generation. In Nigeria, escalating energy costs, the introduction of supportive regulatory frameworks, and national climate commitments have strengthened the economic and policy rationale for large-scale solar PV development. This article examines the technical, planning, environmental, and regulatory considerations associated with commercial-scale ground-mounted solar PV installations. It situates the analysis within Nigeria's Climate Change Act (2021), Renewable Energy Master Plan (REMP), National Renewable Energy and Energy Efficiency Policy (NREEEP), and the National Renewable Energy Action Plan (NREAP). The study reviews planning requirements such as environmental impact assessment, agricultural land classification, landscape and visual impact, biodiversity implications, heritage management, security needs, and community engagement. It also evaluates site selection criteria, construction requirements, ecological assessments, drainage management, glint and glare analyses, and electricity generation capacity reporting. Findings demonstrate that while solar PV farms provide major environmental and socio-economic opportunities, their successful delivery depends on rigorous planning, landscape-sensitive design, compliance with policy frameworks, and robust ecological and security considerations. The article offers comprehensive guidance for planners, developers, policymakers, and stakeholders involved in Nigeria's transition toward low-carbon energy systems.

1. INTRODUCTION

Escalating energy expenses, along with the backing of the Feed-in Tariff (FiT) and Renewable Obligations Certificates, have markedly enhanced the economic feasibility and appeal of

installing solar photovoltaic panels. These installations may be fixed on roofs or walls, or they may be standalone or ground-mounted. This article offers optimal planning assistance about the development of large ground-mounted arrays, outlining planning concerns and criteria. The potential energy that can be extracted from solar radiation is frequently undervalued. The UK receives a substantial quantity of solar energy, averaging up to 60% of the solar energy received at the equator annually. This is comparable to the annual output of 1,000 power plants

For planning purposes, stand-alone solar PV installations refer to those that are not physically affixed to a building, although they may be connected to supply electricity to a building. This represents an alternative interpretation of the FiT, wherein installations must not only be physically detached from a building but also must not be wired to supply energy to an occupied structure; instead, they are directly connected to the electricity grid.

2. LITERATURE SURVEY

Ground-mounted solar photovoltaic farms have emerged as critical infrastructures in the global movement toward sustainable and low-carbon energy systems. With decreasing module costs and improved efficiencies, countries across Africa, Europe, and Asia have adopted solar PV installations as part of broader decarbonisation policies (International Energy Agency [IEA], 2020). The United Kingdom, Germany, Italy, Spain, Morocco, and Nigeria have implemented large-scale PV farms to expand grid capacity and diversify their energy mix (REN21, 2023). Ground-mounted systems—unlike rooftop installations—offer scalability, easier maintenance, and higher electricity yields due to optimal orientation and tilt angles.

Solar PV adoption in Nigeria has accelerated due to chronic energy shortages, dependence on fossil fuels, and rising grid instability. Nigeria receives an average global horizontal irradiation (GHI) of 4–7 kWh/m²/day, making it one of the most solar-endowed nations in Africa (Shaaban & Petinrin, 2014). Despite this potential, deployment has historically been slow due to inadequate regulatory support, limited financing, and infrastructural constraints. However, the Climate Change Act (2021) and the National Renewable Energy and Energy Efficiency Policy (NREEEP, 2015) have played transformative roles in shaping Nigeria's renewable energy trajectory.

The Climate Change Act (2021) established a legally binding framework for reducing greenhouse gas emissions, instituting a National Council on Climate Change, and implementing carbon budgeting mechanisms. It mandates a national pathway toward net-zero emissions between 2050 and 2070, aligning Nigeria with global climate governance under the Paris Agreement (Federal Republic of Nigeria, 2021). The Act strengthens investor confidence by formalising climate governance structures and institutional responsibilities.

The Renewable Energy Master Plan (REMP) outlines progressive targets aimed at increasing renewable electricity to 23% by 2025 and 36% by 2030 (Energy Commission of Nigeria [ECN], 2016). The NREEEP complements this by detailing policies for promoting renewable energy technologies (RETs), encouraging private sector involvement, and establishing technical standards (ECN, 2015). These frameworks identify solar PV as a core driver of Nigeria's transition due to its modularity, accessibility, and declining cost trends.

NREAP provides a detailed implementation roadmap for NREEEP, including incentives such as low-interest loans via the Bank of Industry and enabling frameworks for off-grid and on-grid solar systems (ECN, 2016). Together, these policies aim to diversify energy sources, reduce fossil fuel dependence, strengthen rural electrification, and promote inclusive green

growth.

Large ground-mounted PV farms require careful land selection to minimise agricultural, ecological, and visual impacts. Studies highlight the need to prioritise brownfield, degraded, or low-grade agricultural lands to avoid competition with food production (Hernandez et al., 2015). Nigeria's land evaluation aligns with global best practices by discouraging development on high-grade agricultural lands (Classes 1, 2, 3a), unless impacts are minimal and reversible.

Environmental Impact Assessments help determine whether proposed solar developments may significantly affect biodiversity, soil quality, hydrology, or landscape character. International guidelines emphasise cumulative impact analyses, especially where multiple solar projects exist in proximity (Bureau of Land Management, 2020). In Nigeria, EIAs are guided by the Environmental Impact Assessment Act (1992), requiring detailed screening and scoping, especially in sensitive ecosystems.

Ground-mounted PV arrays alter land cover and can impact scenic quality. European research indicates that visual intrusion is often the most contentious issue in planning applications (Turney & Fthenakis, 2011). Nigeria's LVIA procedures—supported by local landscape character assessments—ensure developments maintain rural aesthetics by preserving hedgerows, mature vegetation, and avoiding prominent ridgelines.

Solar farms can produce both negative and positive ecological outcomes. Habitat disturbance, species displacement, and fragmentation are common risks (Lovich & Ennen, 2011). However, solar farms can also provide ecological co-benefits, including grassland restoration, pollinator habitats, and controlled grazing practices. Nigeria's planning frameworks encourage biodiversity integration through buffer zones, eco-friendly fencing designs, and species-specific mitigation—especially for bats, reptiles, dormice, and avifauna.

Construction activities require detailed planning to protect soil structure, prevent erosion, and preserve agricultural viability for post-decommissioning restoration. Best practices emphasise temporary construction compounds, separate storage of topsoil/subsoil, minimal trenching, and avoidance of mass concrete foundations (Solar Energy UK, 2021). Nigeria's planning guidelines similarly advocate reversible installations, including pile-driven foundations and avoidance of permanent earthworks.

Solar farms are high-value targets for theft and vandalism. Research indicates that remote sites lacking surveillance are particularly vulnerable (Haakana et al., 2017). Recommended strategies include SEAP-compliant security fencing, monitored CCTV, access control, layered security zones, and covert panel marking for traceability.

Glint and glare assessments are increasingly mandated in solar farm applications, particularly near airports or major roads. PV modules are designed to absorb light, but reflections may still occur (Ho et al., 2015). Nigeria's Civil Aviation Authority provides interim guidance on siting solar facilities near aerodromes to minimise aviation hazards.

Global studies demonstrate that community acceptance improves significantly when developers provide early consultations, transparent communication, and local benefit schemes (Walker & Devine-Wright, 2008). Nigerian communities stand to gain from employment creation, environmental trusts, local equity ownership, and improved rural electrification.

Understanding installed capacity, capacity factors, and annual energy yield is essential for evaluating the contribution of solar farms to national energy objectives. Capacity factors for utility-scale solar PV typically range between 18% and 26% depending on location (IEA, 2020). With Nigeria's high solar irradiance, projected yields can significantly strengthen national grid supply.

3. CONTEXT OF RENEWABLE ENERGY POLICY

At the national level, various statutory and non-statutory policy drives and initiatives pertain to the evaluation of planning applications for solar energy. The Climate Change Act 2021 is a Nigerian statute designed to build a legal framework for addressing climate change through the implementation of a low-carbon and climate-resilient development strategy. Essential provisions encompass the establishment of a national objective for net-zero emissions by 2050 to 2070, the formation of a National Council on Climate Change, the creation of a Climate Change Fund, and the implementation of a carbon price mechanism. The Act requires ministries, government organisations, and commercial companies to adhere to its stipulations.

3.1 Essential stipulations and objectives of the Climate Change Act 2021

The Act sets a national objective of attaining net-zero emissions by the years 2050 to 2070. The National Climate Change Action Plan mandates the government to formulate a national action strategy and establish a five-year carbon budget with specified annual objectives. The National Council on Climate Change is designed to implement the action plan, manage the Climate Change Fund, and coordinate climate efforts.

The Act establishes a specific fund to facilitate the operations of the Council and other climate-related initiatives. The carbon tax requires the establishment of a framework to regulate greenhouse gas emissions in conjunction with the Federal Inland Revenue Service (FIRS). The legislation is applicable to all Federal government ministries, divisions, and agencies (MDAs), in addition to public and private businesses in Nigeria.

The Goals of the act are:

- To establish a legal framework enabling Nigeria to fulfil its climate objectives and obligations, including the Paris Agreement and its Nationally Determined Contributions (NDCs).
- To promote low-carbon development and an environmentally sustainable framework.
- To advocate for inclusive green growth and sustainable economic advancement.
- To integrate climate change into national development priorities.
- To recognise and mitigate climate-related risks and vulnerabilities.

The Nigeria Renewable Energy Roadmap outlines a set of strategies to achieve the legally mandated objective established in the Climate Change Act 2030. The plan anticipates that over 30% of the Nigerian's electricity will be produced by renewable sources. The Roadmap indicates that the government perceives solar PV as having the capacity to constitute a substantial component of the renewable energy generation portfolio.

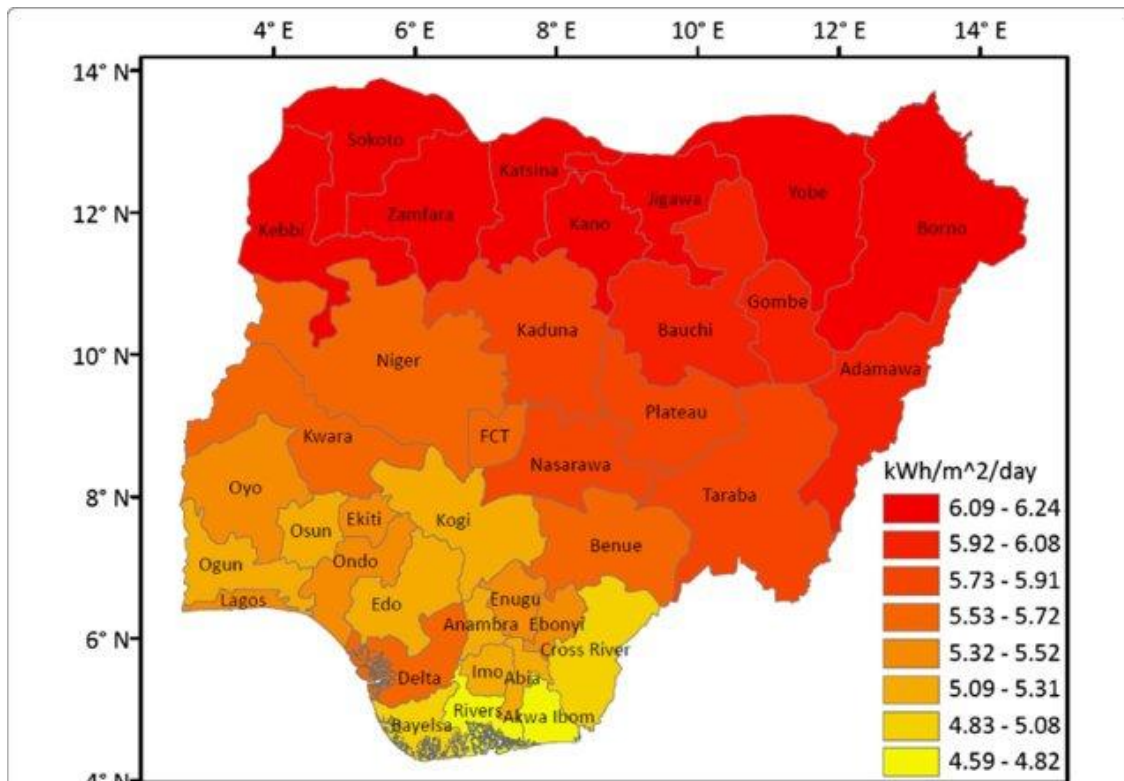


Figure 1. Map of Nigeria illustrating the global solar radiation (Gh) on the ideally inclined plane across the states. Source:

https://www.researchgate.net/publication/353690334_Whistleblowing_on_photovoltaic_operations_in_Nigeria_panacea_for_sustainable_development/figures?lo=1&utm_source=google&utm_medium=organic.

3.2 National Planning Policy

Nigeria's National Planning Policy for renewable energy is articulated in frameworks such as the Renewable Energy Master Plan (REMP) and the National Renewable Energy and Energy Efficiency Policy (NREEEP), which seek to enhance the utilisation of renewable energy sources, including solar and biomass, diversify the national energy portfolio, encourage private sector investment, and augment rural electricity access. These plans offer strategic frameworks, establishing objectives, delineating incentives, and fostering a conducive climate for renewable energy advancement within the context of overarching national development objectives.

Principal policy documents

- Renewable Energy Master Plan (REMP): This is a strategy framework comprising particular, time-sensitive initiatives aimed at advancing renewable energy development.
- National Renewable Energy and Energy Efficiency Policy (NREEEP): This policy establishes the overarching framework for advancing renewable energy and energy efficiency in Nigeria.
- National Renewable Energy Action Plan (NREAP): This plan delineates the implementation strategy for the NREEEP, specifying definitive policies, regulations, and methods to attain the established targets.

3.2.1 Objectives and aims

- The REMP seeks to substantially augment the proportion of renewable electricity in the overall generation mix, targeting 23% by 2025 and 36% by 2030.

- Enhance rural accessibility: Due to the low rates of rural access, renewable energy technologies are seen as optimal for delivering decentralised electricity to rural populations.
- Diversify the energy portfolio: The policies seek to diminish the excessive dependence on fossil fuels, while oil is anticipated to continue being a significant component of the economy.
- Encourage private sector involvement: The initiatives seek to establish a conducive framework for private sector investment and engagement in the renewable energy sector.

3.2.2 Strategies and initiatives

- The technical and regulatory framework facilitates the establishment of standards, testing, and certification to enhance consumer confidence and expand the market.
- Market expansion: They enable both grid-connected and off-grid operations for renewable energy generation.
- Resource development: The strategy encompasses the creation of a comprehensive resource database to assist investors in making educated selections.
- The NREEEP recognises the difficulty of intermittency in energy storage and advocates for solutions such as battery storage to enhance the flexibility of energy systems.
- Biomass integration: The policy encompasses targeted initiatives to utilise and incorporate non-fuelwood biomass resources into the energy portfolio.

3.2.3 The Economic Framework

Nigeria's National Planning Policy framework, formulated through initiatives such as the Renewable Energy Masterplan (REMP) and the National Renewable Energy Action Plan (NREAP), delineates the financial landscape for renewable energy by fostering an enabling environment, encouraging private sector investment, and offering targeted incentives. Essential actions encompass the creation of financial instruments, the promotion of low-interest loans for small-scale initiatives, and the resolution of issues such as elevated interest rates and the scarcity of long-term credit for renewable energy.

3.2.4 Monetary context and motivations

The policy framework seeks to establish a conducive atmosphere for sustainable energy supply by delineating explicit targets, deadlines, and strategic methodologies for renewable energy advancement.

The government intends to offer incentives to stimulate investment and expansion in the renewable energy sector. The National Renewable Energy Action Plan (NREAP) outlines particular initiatives, including the provision of low-interest soft loans via the Bank of Industry for small-scale renewable energy enterprises.

Market development: The strategies acknowledge the necessity of expanding the renewable energy market and facilitating private sector involvement in fulfilling the nation's renewable energy objectives. The strategy recognises financial obstacles, such as banks' hesitance to finance unconventional projects and elevated interest rates, and aims to mitigate these issues through targeted policies and incentives.

Methodical strategy

- Private sector engagement: The active involvement of the private sector is a fundamental aspect of the policy, aimed at establishing an economically sustainable market for renewable energy.
- Renewable energy development aligns with national objectives, including enhancing

electricity availability, encouraging economic growth, generating employment, and alleviating poverty.

- The National Energy Masterplan offers a cohesive framework for optimising Nigeria's energy resources to satisfy increasing domestic demand and establish the nation as an energy powerhouse in West Africa.
- Commercial-scale ground-mounted solar photovoltaic systems. Extensive, centralised solar photovoltaic power systems, predominantly at the multi-megawatt scale, have been established to provide electricity for local or regional grids in several countries, including Nigeria, Morocco, Germany, Switzerland, Spain, and Italy. Recently, substantial solar photovoltaic projects have been established in England and Wales. This handbook is to offer planning information regarding large-scale commercial ground-mounted solar photovoltaic installations.
- Ground-mounted solar PV projects over 50 kWp should preferably employ previously built land, brownfield sites, polluted land, industrial land, or agricultural land classified as 3b, 4, and 5, while avoiding the use of "Best and Most Versatile" cropland if feasible. The chosen land must prioritise the preservation of visual aesthetics, uphold natural beauty, and be primarily level, effectively concealed by hedges and tree lines, while minimising adverse effects on adjacent residential properties or roadways.

3.3 Pre-application considerations.

Engagement with the Local Planning Authority and the local community is advised at an initial phase. The developer should engage the local community throughout the pre-design conceptual phase, preferably through a local exhibition or presentation to solicit and document community feedback.

3.4 Environmental Impact Assessment (EIA)

Large-scale solar photovoltaic arrays are not explicitly enumerated in Schedule 2 of the EIA Regulations 1999; the environmental impact of such developments, whether beneficial or detrimental, is contingent upon their location.

3.5 Environmental Impact Assessment Screening

The proposal should initially be evaluated according to the selection criteria outlined in Schedule 3 of the EIA Regulations. An Environmental Impact Assessment (EIA) is often required for Schedule 2 developments if the solar photovoltaic project is situated in an environmentally sensitive or vulnerable area. It is essential to assess if the anticipated environmental impacts of the development will be substantial in that specific site. To assess the significance of a development's effects, it is essential to consider the visual impact on landscape character, particularly regarding the installation of a solar PV farm, as well as the potential cumulative effects with any existing or approved developments. This should encompass scenarios involving many applications for solar PV development that must be evaluated collectively. All opinions articulated by consultees must be considered. Consultation with experts is advisable where there is uncertainty regarding the impact of a development on a 'sensitive region' as delineated in the EIA Regulations.

3.6 Formulating Performance Agreements

To enable the Local Planning Authority to provide adequate resources to address demand, applicants may consider entering into a Planning Performance Agreement (PPA) with the Local Planning Authority. The PPA mandates that developers provide a financial contribution to the Authority, which will thereafter allocate these monies to assign staff resources for the planning proposal submitted by the developer. The PPA mandates the Authority to collaborate with the

developer during the pre-application phase, facilitate public comment and involvement, and maintain communication with the developer throughout the planning application process.

4. PREREQUISITES FOR APPLICATION

4.1 Application Fee for Planning

No national advice exists regarding the fee category for large-scale ground-mounted solar photovoltaic installations. Typically, such applications are classified under Category 5 (erection, alteration, or replacement of plant or machinery) of the Town and Country Planning (Fees for Applications and Deemed Applications) as amended. Nonetheless, it is recommended that this be verified with the pertinent Local Planning Authority.

Essential information may encompass:

- A site plan (1:1250 metric scale)
- A site/block layout at a 1:500 metric scale
- Altitudes
- Design and Access Statement
- A corroborative declaration
- Fencing specifications and pertinent details (if appropriate)
- Specifications of electrical grid connection
- Specifications of any further structures or edifices envisaged, including elevations
- A relevant ecological assessment
- A landscape and visual evaluation if the application site is located inside or would affect an Area of Outstanding Natural Beauty, National Park, or World Heritage Site (see to Appendix A).
- A historic environment statement, if relevant (see to the above).
- Assessment of impact on agricultural land if relevant.
- Evaluation of Flood Risk.
- Finalized the 'Electricity Generating Capacity' form (refer to Appendix B).
- Construction Traffic Management Plan (CTMP)
- Required application fee.
- Application Fee for Planning

No national guidelines exist regarding the fee classification for large-scale ground-mounted solar photovoltaic projects. Typically, such applications are classified under Category 5 (erection, alteration, or replacement of plant or machinery) of the Town and Country Planning (Fees for Applications and Deemed Applications) as amended. Nevertheless, it is advisable to verify this with the pertinent Local Planning Authority. The most recent fees can be computed online via the Planning Portal Online Fee Calculator by selecting Yes > Full Planning Consent > Calculate > Non-Residential > Erection, alteration, or replacement of plant or machinery (inputting site area in hectares). Refer to the details below concerning the calculation of the site area.

4.2 Determining the Site Area for fee assessment

As a directive:

- If the solar panels are situated near a field boundary and there is an existing or proposed fence, the planning application area must encompass these field boundaries.
- If the solar panels are situated more than 50 meters from the field boundaries, where a distinct fence is envisaged, the planning application boundary should encompass the

proposed solar panels, with an additional planning application area surrounding the fenced region. In such cases, it would be imprudent for the application area (and planning application cost) to encompass substantial portions of land where no development is intended. In the absence of a proposed fence and with solar panels situated centrally inside a field, distanced from the field limits, the planning application boundary should encompass the proposed array and any adjacent ancillary works, such as access tracks.

- It is the responsibility of the applicant to ensure that all proposed developments are encompassed within the boundaries of the planning application.

4.3 Comprehensive Planning Approval

Outline planning approval cannot be approved for a planning application categorised under section 5 of the aforementioned fee regulations. Only comprehensive planning proposals will be validated. Certain aspects, such as the precise dimensions or model of the solar panel, may be 'reserved'; nonetheless, adequate specific information must accompany any planning application to enable the Local Planning Authority to thoroughly assess the application.

The most recent fees can be computed online via the Planning Portal Online Fee Calculator by selecting Yes > Full Planning Consent > Calculate > Non-Residential > Erection, alteration or replacement of plant or machinery (inputting site area in hectares). Refer to the details below concerning the calculation of the site area.

4.4 Considerations for Planning Applications

- a. Site Levelling Operations: Attention must be directed on the prevailing site topography. Any proposed site levelling works to enable the building of a solar panel array should be addressed during the pre-application phase and thoroughly specified in the planning application.
- b. Development Concerning Current Land Use: Ideally, ground-mounted large-scale photovoltaic arrays should be situated on previously built land, brownfield sites, polluted land, industrial land, or agricultural land classified as 3b, 4, or 5. Although there is no prohibition against ground-mounted large-scale photovoltaic arrays on sites classified as agricultural 1, 2, and 3a, or designated for their natural beauty or recognised ecological or archaeological significance, it is improbable that planning permission will be approved if there is a substantial impact on these designations.

4.5 Evaluation of the Effects on Agricultural Land

Paragraph 112 of the National Planning Policy Framework mandates that the presence of best and most versatile agricultural land, classified as grades 1, 2, and 3a, must be considered in conjunction with other sustainability factors. The NPPF favours directing development away from land classified as 3b, 4, and 5; yet, paragraph 28 acknowledges the necessity of supporting agricultural land diversity to sustain agricultural enterprises.

This policy stance must be considered when selecting locations for extensive solar panel development. When development is proposed on agricultural property, it is advantageous for the applicant to suggest a project completion date to illustrate the transient character of the solar farm. The developer should conduct the following procedures when contemplating the placement of a large-scale solar PV project on agricultural property. Should a planning application be submitted afterward, it must include the pertinent information outlined in the following steps. Agricultural Land Classification: safeguarding the finest and most adaptable agricultural land.

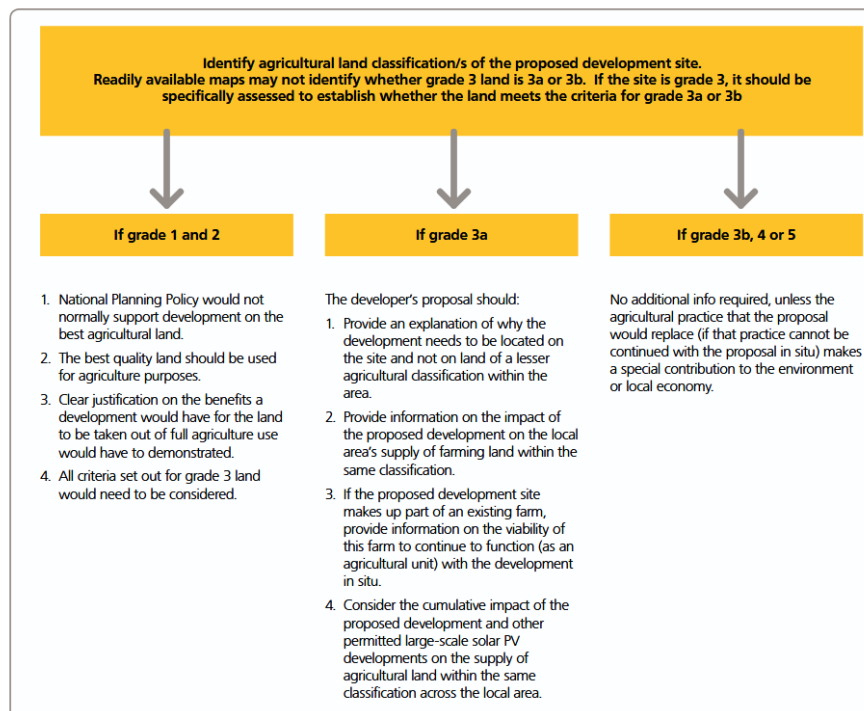


Figure 2. Procedures for developers regarding agricultural land classification

4.6 Landscape Maintenance

Vegetation will proliferate beneath the solar panels, necessitating maintenance to prevent the area from becoming overrun with invasive weeds and to facilitate the eventual restoration of the property, typically for agricultural purposes. Numerous strategies exist for vegetation management, including mowing, trimming, spraying, and mulching. Application of sprays should be minimised whenever feasible, and mulching extensive areas may provide technical difficulties and potentially enhance the landscape or visual impact of a development concept. Several of these management strategies are considered unsustainable, especially on sites up to 15 hectares, and there is a strong inclination, regarding both food production and the rural landscape, to maintain agricultural usage on the site.

During periods of growth, controlling grazing should be promoted whenever feasible. Cattle, horses, pigs, and goats are likely to be excessively 'physical' with the solar arrays; however, sheep, chickens, or geese should be permissible. To enable grazing within the solar farm, it is recommended that solar panels be installed at a minimum height of 700mm above ground level, with all cabling adequately safeguarded.

4.7 Construction Site

The establishment of a large-scale solar array will necessitate the transportation and storage of construction materials, equipment, machinery, and office/welfare facilities. A temporary construction compound will likely be necessary. These compounds must be strategically positioned to mitigate environmental or amenity impacts, and any planning application should include specifications for their dimensions and placement. Topsoil and subsoil must be excavated from these areas and retained on-site for reinstatement after the building activities are concluded. Any planning application must include details regarding soil stripping, storage, and replenishment, along with the expected duration of the construction compound's operation.

4.8 Soil Excavation, Preservation, and Reinstatement

The establishment of a substantial solar installation will likely necessitate the excavation of soils related to construction compounds, access roads, cable trenching, and similar activities. In instances of soil stripping, topsoil and subsoil must be removed, stored, and reinstated separately to mitigate soil degradation and ensure optimal conditions for site rehabilitation. Every planning application must include a system for soil stripping, storage, and replacement, which should be strictly followed throughout the site development process.

4.9 Access Routes

Solar panel installations established on agricultural property should:

- a. strive to reduce disruption to the agricultural terrain;
- b. be transient, removable, and 'reversible'; and
- c. reduce their landscape and visual impact as well as their effect on the rural environment.

The establishment and utilisation of access tracks should be minimised to the utmost extent. A minimum of one track connecting the inverters may be required to facilitate the swap of inverters and the replacement of heavy gear. Agricultural vehicles, such as tractors, quad bikes, and 4WDs, must be able to service the facilities daily without requiring the construction of access tracks on the site. A buffer zone beyond 5 meters between hedges and solar panels is preferable to enhance ecological and biodiversity prospects, if feasible.

4.10 Security Fencing and Lighting

Applicants must exert significant effort to reduce the landscape and visual impact of solar photovoltaic systems. Although there is a recognised necessity to maintain the necessary security of solar PV systems, it would be regrettable if such precautions led to an unacceptable impact on the landscape or visual aesthetics. Candidates must:

- a. Reduce the utilisation and elevation of security fencing.
- b. Employ existing elements, such as bushes or landscaping, to obscure security fencing;
- c. Utilise natural elements, such as the installation of vegetation, to enhance site security.
- d. Reduce the utilisation of security illumination. All lighting must employ passive infra-red (PIR) technology and be designed and placed to avoid glare, light pollution, and effects on biodiversity, particularly concerning bats (see to the ecology section).
- e. implement suitable steps to enable ongoing access for larger species, including badgers and foxes.

In certain cases, specialised fence may be required to restrict deer access. Deer fencing can be significantly less obtrusive than alternative fencing methods and should be contemplated wherever feasible. Planning applications must provide comprehensive descriptions and specifications of all security and lighting installations to facilitate an accurate landscape, visual, and ecological assessment of the design. The placement of pole-mounted CCTV facilities should be meticulously evaluated to reduce visual and landscape effect. Such constructions should be avoided in exposed areas if feasible.

The subsequent details are derived from a general survey conducted in Nigeria.

The commercial-scale generation of power from solar energy utilising photovoltaic panels in Nigeria presents novel hazards and problems, necessitating measures to safeguard the site and equipment from criminal activities. Due to the novelty of this research, there is presently no available crime data from Nigeria to provide crime prevention recommendations. Law

enforcement experience suggests that situating substantial amounts of costly solar panels in remote areas without sufficient security measures may entice criminals, resulting in the theft of the panels and related infrastructure. The primary threat will originate from organised gangs employing heavy-duty tools and vehicles to extract substantial quantities of the panels. The stolen panels are likely to be relocated from the crime scene prior to being resold.

Site: A significant issue from a policing perspective, while evaluating appropriate locations for solar farms, will be the measures implemented to safeguard the site against illegal vehicle access. Comprehensive evaluation of the site's natural fortifications, such as steep gradients, substantial hedging, and rivers, should be undertaken. The site's boundary barrier should be positioned at a suitable distance from the panels to deter vehicles from parking against the boundary and facilitating the manual theft of panels.

Site Access: The solar company or site owner will necessitate vehicular access to the location. The physical security protecting this access must be resilient to withstand significant assaults, as these locations are likely to be isolated and devoid of natural observation. Protection of the access road at two distinct points should be prioritised;

- a. at the actual entry to the site and;
- b. Remove authorised vehicles from the designated entry to maintain a considerable distance from the location.

The security of solar farms must be thoroughly evaluated by all participants in the design process. Consequently, all planning applications must have comprehensive information of the security provisions within the Design and Access Statement. Security measures at each place must be evaluated on a site-specific basis. They will undoubtedly be influenced to some extent by factors such as the prevailing terrain and local zoning restrictions. The fundamental idea of crime prevention is to establish many layers of defence for that which requires safeguarding. Solar farms will likely necessitate both physical barriers, such as fences or ditches, and the implementation of suitable technology, such as CCTV. The following information encompasses essential crime prevention considerations for all applicants.

Perimeter Security and Access Control: If perimeter fencing is employed, it must be a verified security fence. It is advisable to install fencing that has been tested and authorised according to current Nigerian Government regulations. Fencing that complies with SEAP (Security Equipment Approval Panel) class 1-3 may be the most suitable. Non-specialist fencing is likely to provide, at most, just nominal resistance to invaders. Planting adjacent to any fencing is permissible, provided it does not adversely impact site surveillance. Landscaping methods, including ditches and berms (bunds), may be suitable in some situations. To effectively halt cars, meticulous design is needed. The police can offer additional particular guidance regarding the design of such defences upon request. There should be a minimum of automobile access points to the site, preferably limited to a single entry. Clearly, such access points will provide the most apparent opportunities for criminals and hence necessitate a powerful and sufficient defence. Consideration should also be afforded to the broader access difficulties around any site. If the area adjacent to the site is under the same ownership, may security be enhanced by upgrading gates and similar measures? This presents multiple layers of complexity for the criminal to navigate.

Electronic Security: A vast array of electronic security options exists. For the majority of sites, it is highly probable that this will assume a significant role. A thorough site-specific assessment should be conducted to determine the appropriate technology to guarantee the system is suitable for its intended purpose. This evaluation for CCTV is typically referred to as an Operational

Requirement (OR). A clear example would be to determine the effectiveness of the CCTV during nighttime at these sites. Deploying CCTV or other security measures is likely to yield no benefit unless they are monitored or capable of providing immediate alerts; furthermore, it raises the question of who would respond to such alerts. CCTV that merely records is likely to possess minimal utility.

Alternative Considerations: The inclusion of site security staff in various capacities should be evaluated, particularly for specific responses to site alarm activations. The utilisation of security bolts to fasten photovoltaic panels and locked enclosures to safeguard inverters, among other components. Clearly marking individual solar panels would diminish their resale and reuse potential, so serving as an additional deterrent and aiding in future detection. Covert security markings should further be employed.

4.11 Soil Anchors

Solar photovoltaic installations established on agricultural land should be 'reversible', facilitating the site's restoration to a more intense agricultural use. Consequently, intrusive development, including trenching and foundations, should be limited, and the utilisation of mass concrete should be eschewed. Solar PV arrays should, where feasible, be built using pile-driven or screw foundations, or pre-molded concrete blocks (shoes), and designed for simple removal. Footwear may be mandated in archaeologically sensitive regions. When proposing 'pile' driven foundations, applicants should assess the development consequences on adjacent noise-sensitive properties.

5. MONITORING AND NAVIGATION

Certain solar photovoltaic arrays will track the sun's daily trajectory to optimise solar energy absorption. These devices, referred to as 'trackers,' optimise solar gain; however, they entail high installation and maintenance costs. Certain solar photovoltaic arrays will remain stationary. These systems are more economical to build and maintain; nevertheless, due to their inability to track the sun's trajectory, they are less efficient than 'trackers.' A compromise is established with certain solar photovoltaic arrays that are predominantly stationary but may be relocated quarterly to accommodate seasonal variations in the sun's trajectory across the sky. The installed solar PV array type and the degree of any tracking will influence the landscape and visual assessment; thus, the planning application must explicitly specify the planned array type.

The influence of 'trackers' on grazing animals, such as sheep, must be meticulously evaluated to prevent these animals from becoming ensnared in any moving components. The alignment of stationary solar photovoltaic panels should also be taken into account. Recently, developers are evaluating the benefits of altering the orientation of panels across the development to optimise electricity output over the year and day. These details should be delineated in the planning application and evaluated in the landscape effect assessment.

5.1 Topographical / aesthetic influence

The visual impact of a solar PV farm is expected to be one of the most significant effects of such development. Developers may be drawn to south-facing locations, where solar exposure is maximised. Nonetheless, such places may possess significant agricultural value and are likely to be more prominent within the broader landscape. Solar PV farms are considered a temporary land use (see Duration of Planning Permission at the conclusion of the Guidance), and consequently, the removal of existing vegetated field boundaries, including hedges, will not be authorised, since this would permanently modify the landscape character of the site.

The development must consider both its architectural layout and future maintenance plans to ensure the preservation and expansion of vegetation along these significant borders, including the potential for individual trees within these boundaries to reach maturity.

The landscape and visual impact must be meticulously evaluated during the pre-application phase. The Local Planning Authority Landscape Officer must be consulted promptly, and mitigation measures should be proposed if needed. The information required for a Landscape and Visual Impact Assessment is detailed in Appendix A.

Existing hedges and established vegetation, including older trees, should be preserved if feasible. Arboricultural and hedgerow preservation must be ensured during building activities. The proposed development's effect on existing trees and hedges must be assessed using a tree survey (according to BS 5837) and/or a hedge evaluation where necessary.

Buildings intended to accommodate electrical switchgear, inverters, and similar equipment must be designed and erected to reduce their landscape and visual impact, with construction materials chosen to align with the local landscape environment. When utilising a pre-fabricated structure, it is essential to contemplate the necessity of concealing the building with greenery.

5.2 Aggregate Effect

The Local Planning Authority must keep a comprehensive record of all planning applications pertaining to large-scale solar PV systems, as well as a record of all planning decisions made. Prospective applicants should consult their Local Planning Authority to examine these data promptly, ensuring that the cumulative impact of the development is assessed and addressed throughout the preparation of any planning application.

Thorough evaluation must be conducted about the influence of current or planned vegetation to guarantee that any resulting shade of solar panels does not necessitate future trimming or removal of said vegetation.

5.3 Ecology

The effects on ecology will be contingent upon the site's natural attributes and its sensitivity to proposed alterations. Solar photovoltaic arrays may result in habitat loss, fragmentation, change, and species displacement. Nevertheless, solar PV arrays may also provide environmental benefits, such as fostering habitats through preserved grasslands over extended periods, wildflower meadows, taller hedgerows, and woodlands, among others.

The National Planning Policy Framework delineates the national approach to ecology within the planning process and articulates certain guiding concepts. It is essential to evaluate the effects that may arise during the building, operation, and decommissioning phases of a project.

Design must be guided and shaped by ecological evaluations, such as phase 1 habitat surveys and protected species assessments. Concerns requiring specific evaluation encompass ground-nesting avifauna, wintering birds, chiropterans, dormice, reptiles, and badgers. Engaging an advising ecologist during the design phase can guarantee the mitigation of detrimental consequences and the maximisation of biodiversity gains. Protected species surveys are contingent upon the season; therefore, it is prudent to consult an ecologist at an early stage.

The assessment must incorporate a 'desk study' of current ecological records, an appraisal of

the anticipated consequences of the solar farm on ecological features, describe mitigation measures to prevent or limit these impacts, and enumerate any additional surveys needed. The primary effects and necessary mitigating measures are expected to be:

- a. .Illumination - security lights may impact bat populations. It is recommended that lights be utilised only when absolutely essential. If illumination is required, it should be reduced and directed away from hedges, woodlands, and scrub. A bat survey is necessary to determine any additional mitigation required and whether illumination is permissible on the site.
- b. Overhead and subsurface cables may negatively affect biodiversity. Cable routes must be meticulously planned in collaboration with the consulting ecologist.
- c. In construction, it is recommended that existing hedges be preserved in their entirety and that no new hedge gaps be established. Should any hedges or bush be removed, more surveys for dormice and reptiles may be required. Pile driving may impact surrounding badgers; this necessitates a badger survey, and a licence may be required.
- d. .It is recommended that substantial buffer strips (a minimum of 4-5 meters) be maintained between perimeter fencing and hedges. The fencing must permit access for badgers, reptiles, and other species to the site, while also accommodating grazing sheep, as stipulated in the ecological study. A gap should be maintained around the entire base of the fence to permit access for small mammals and reptiles, with larger openings or gates for badgers at appropriate intervals.
- e. Enhancement, Management, and Monitoring – Solar farms can augment the biodiversity worth of a site if the area was previously subjected to rigorous management. Grazing by sheep or an autumn mowing with the removal of grass clippings could enhance the botanical diversity of the area. The ecological consultant must delineate an appropriate management strategy for each instance, considering the shading effects of the solar panels. Hedges must be managed effectively and may be laid to minimise gaps. Proposed improvements should augment and expand current habitats or establish new significant habitats, such as cultivated strips or plots for rare arable flora, rough grassland margins, bumblebee plant mixtures, and wild bird mixes. It is recommended that an ecological monitoring program be established to assess the impacts on the site's flora and specific features, such as bats and wintering birds. The monitoring results will subsequently guide any necessary modifications to the management or grazing regime.

5.4 Checklist for advising on possible nature conservation impacts:

- a. Can the development site, individually or collectively, affect a designated site and its designation objectives?
- b. Is the habitat or species sensitive to alterations that may arise from a solar array project?
- c. Is the site capable of effectively integrating land uses and providing environmental advantages?
- d. Are the proposed mitigation actions sufficient and likely to be effective?
- e. Is post-construction monitoring essential?
- f. Have the implications been adequately evaluated in the Environmental Impact Assessment/Hazard Risk Assessment or other environmental evaluations? Do we concur with the conclusions?
- g. Are there prospects for environmental improvement, including the establishment of additional natural screening elements or the management of land and margins for conservation objectives?
- h. Are enhancing measures suitable and do they further broader objectives in the region, such as the Biodiversity Action Plan (BAP) initiatives?

Solar PV farms can enhance biodiversity, making it essential to optimise the environmental

benefits of the land on which they are situated.

5.5 Heritage Environment

The effects of solar PV advancements on the historic environment will necessitate expert evaluation in the majority of instances. Solar photovoltaic developments may impact heritage assets, including sites, monuments, buildings, and landscapes, both above and below the surface. Above-ground impacts may encompass the effects of applications on the settings of Listed Buildings, provided the setting is included in the listing, Scheduled Monuments, and the Historic Landscape Character. Subsurface effects may encompass direct consequences on archaeological deposits due to ground disturbances linked to trenching, foundations, fencing, temporary haul routes, and similar activities. Equally, findings may be safeguarded by a solar PV farm, as the location is exempt from conventional tillage, and the use of shoes or low-level piling is mandated.

If a proposed development site contains or may contain heritage assets of archaeological significance, local planning authorities should mandate that developers provide a suitable desk-based assessment and, if required, a field evaluation. This should be conducted in collaboration with the local authority planning team or historic environment officer, who can furnish a brief for the necessary expert assessment or evaluation work. Results from these assessments will be necessary as supporting documentation prior to the validation of applications, as stipulated in The National Planning Policy Framework. Applications must consider the outcomes of historic environment assessments in their design, particularly through the careful planning of installations. Opportunities to enhance the management of impacted assets or to optimise the conditions of designated sites should be recognised.

5.6 Drainage, Surface Water Discharge, and Flooding

The Environment Agency has indicated that, owing to the scale of solar PV farms, planning applications must include a Flood Risk Assessment. This must take into account the effects of drainage. The drainage of solar PV panels into the existing ground will generally have a negligible impact, thus this should not be a burdensome requirement.

Permeable access tracks should be utilised where necessary, and localised Sustainable Urban Drainage Systems (SUDS), such as swales and infiltration trenches, should be implemented to manage runoff as advised. Due to the transient nature of solar PV farms, sites must be designed or chosen to prevent interference with existing drainage systems and watercourses. It is advisable to refrain from culverting existing watercourses or drainage ditches. When culverting for access is indispensable, it must be evidenced that no feasible alternatives are available, and if necessary, it should be implemented only temporarily during the construction phase.

5.7 Reflection and Shine

Glint may occur as a direct reflection of sunlight on the surface of the solar PV panel. It may be the origin of the visual problems related to viewer distraction. Glare is a persistent source of luminosity, in contrast to diffused illumination. This is not a direct reflection of the sun, but rather a reflection of the luminous sky surrounding it. Glare is markedly less vivid than glimmer. Solar photovoltaic panels are engineered to absorb, rather than reflect, irradiance. Nonetheless, the sensitivities related to shine and glare, as well as the landscape/visual impact and the potential effects on aviation safety, must be taken into account. In certain cases, a glint and glare assessment may be required as part of a planning application. This may be especially significant if 'tracking' panels are suggested, as they may result in varying diurnal and/or seasonal effects.

The possibility for solar PV panels, frames, and supports to possess a collective reflective quality should be evaluated. This evaluation must account for the probable reflecting properties of all materials utilised in the construction of the solar PV farm.

5.8 Community Engagement and Benefit

Community involvement must be regarded as a fundamental component of the development process. The developer should engage the local community throughout the pre-design conceptual phase, preferably through a local exhibition or presentation to gather and document community feedback. A subsequent exhibition or presentation must be organised by the developer several weeks before the submission of the planning application. The second consultation should provide adequate time to gather community perspectives and incorporate them before submitting any final planning proposal. Every planning application must specify the exhibitions or presentations, the opinions or representations received, and how the application was modified or influenced to align with those representations. The developer may also desire to conduct an exhibition or presentation subsequent to the submission of a planning application.

Community Gain - Opportunities for communal advantage should be pursued whenever feasible. Opportunities encompass;

- a. Creation of a local Environmental Trust or Community Benefits Trust, funded annually by the developer for energy conservation initiatives.
- b. Local equity issuance.
- c. Local or community ownership of solar panels.
- d. Investment in the provision and management of Green Infrastructure, particularly at the landscape level.

While community benefits are advocated, it must be explicitly stated that any proposal is not pertinent to the evaluation of any planning application. Neither the fundamental idea of any initiative nor its specific elements may be presented to directly alleviate a particular planning objection to a proposal. The stipulation for community benefit is deemed non-compliant with the Community Infrastructure Levy Regulations 2010 (as modified) and cannot be mandated under planning legislation. Consequently, no significance can be attributed to the incorporation of a community benefit program while evaluating a planning proposal.

5.9 Aviation Security

The Nigerian Civil Aviation Authority (NCAA) has issued recommendations regarding solar energy, including interim instructions for the construction of solar panels in proximity to Nigerian aerodromes.

5.10 Electricity Generation Capacity

Planning applications for commercial-scale solar photovoltaic projects must explicitly specify the installed capacity (MW) of the planned facility. While the NPPF indicates that local authorities should not mandate applicants for energy developments to prove the overall necessity for renewable or low carbon energy, and acknowledges that small-scale projects significantly contribute to reducing greenhouse gas emissions, this is regarded as pertinent background information.

Although it is acknowledged that the efficiency of solar PV panels may diminish over time, the original installed capacity should be specified. The 'capacity factor' and projected yearly production (MWh p.a.) must be included alongside the number of residential premises

equivalent in electricity for Nigeria. An explanatory pro forma table is included as Appendix B. This information will enable the public and elected officials to comprehend the producing capacity of the proposed facility accurately.

5.11 Duration of Planning Authorisation

Solar photovoltaic farms should often be considered a transient utilisation of land. Consequently, it is probable that planning clearances will restrict the length for which the system may be operational. Planning permissions will typically;

- a. Must be executed within a timeframe of three years
- b. Include a timeline for the completion of the construction and commissioning of the project.
- c. Be limited to a temporary duration commencing with the facility's commissioning.

5.12 Tourist Destination/Learning Institution

Applicants should consider, when applicable, the creation and implementation of viewing spaces, explanatory panels, and visitor or educational facilities as components of any development proposal. Although not all solar PV farm ideas are expected to require such facilities, there may be circumstances when such development is suitable.

6. CONCLUSION

Ground-mounted solar photovoltaic farms present a transformative opportunity for Nigeria's pursuit of sustainable, low-carbon energy development. Supported by robust policy frameworks—including the Climate Change Act (2021), NREEEP, REMP, and NREAP—solar PV deployment is positioned to expand significantly over the next decade. Successful implementation, however, requires meticulous planning, environmentally sensitive site selection, comprehensive EIAs, and careful consideration of agricultural, ecological, aesthetic, and security factors. The integration of community engagement, heritage protection, drainage management, and glint-and-glare mitigation further strengthens project viability. As Nigeria confronts rising energy demand, rural electrification deficits, and climate-related vulnerabilities, well-planned solar PV farms can enhance energy security, stimulate economic growth, and contribute meaningfully to national climate commitments. Ensuring compliance with best-practice planning standards will be essential for maximising the social, environmental, and economic benefits of large-scale solar developments.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Appendix A:

Recommendations about the material should be included in a Landscape and Visual Impact Assessment

Standard Solar Farm Evaluation Response

Incorporating landscape considerations into the decision-making process is essential, as the primary environmental consequence of such a development will be its effect on landscape character and visual amenity. The inquiry pertains to the potential for this solar farm project to generate substantial environmental impacts on the landscape, and consequently, whether the Environmental Impact Assessment Regulations are applicable to the application.

Several factors related to solar farm construction may affect the magnitude of affects on landscape character and visual amenity.

- a. Gradient of the site and the adjacent topography,
- b. Scope of the application site,
- c. Dimensions and arrangement of the panels,
- d. Colour of the panel's surrounding frames,
- e. .Management of the soil beneath and between the panels, such as cultivating crops, grazing cattle, or applying mulch to minimise upkeep.
- f. .Boundary enclosure.

This is an illustration of how significance may be assessed, initially concerning landscape character and subsequently about visual effect.

- Evaluation of the influence on landscape character can be categorised as high, medium, or

low, either harmful or helpful, based on the assessment of the:

- erosion of essential components of the pre-development environment;
- Integration of items into the receiving landscape resulting in alterations to the overall landscape character.

Significant impact on landscape character - complete loss or substantial modification of essential components of the pre-development landscape, or the incorporation of elements deemed incongruous with the characteristics of the receiving landscape, or the proposal emerges as a predominant feature within the scene, rendering surrounding elements subordinate, resulting in a transformation of the overall character.

Moderate impact on landscape character - partial loss or modification of one or more key landscape elements prior to development, or the introduction of elements that may be prominent or create a visibly recognisable new feature, yet may not be deemed significantly uncharacteristic within the context of the receiving landscape's attributes.

Minimal impact on landscape character – slight loss or modification of one or more essential elements of the pre-development landscape, or the incorporation of elements that represent a minor aspect of the broader landscape and are consistent with the characteristics of the surrounding landscape.

The sensitivity of the landscape as a resource can be categorised as high, medium, or low, contingent upon the landscape's:

- a. *Character*: What contribution does the site provide to how rge occupants behave? What is the character of the place in its natural state? Does it conform to a discernible pattern of Elements or qualities pertinent to the region? Does the site enhance the area's feeling of identity and uniqueness?
- b. *Quality*: What is the condition of the current landscape?
- c. Is this landscape esteemed by individuals, the local community, and visitors? Are there certain cultural Affiliations? Does the area possess a landscape, ecological, or historical designation? Is the landscape acknowledged at the local, regional, or national level?
- d. *Capacity*: What potential exists for modification in the current framework?
- e. landscape characteristics?
- f. *Significant importance* - a landscape of high quality with esteemed attributes and a favourable character that is especially susceptible to alteration. A landscape of significance or uniqueness at a local, regional, or national level.
- g. *Moderate significance* - typically possesses a favourable character; yet, there may have been deterioration or erosion of attributes, leading to regions with a more heterogeneous character and diminished total worth. Moderately sensitive to change; while certain alterations may be accepted, improper management could be damaging. A landscape of moderate significance or uncommonness at a regional or local level.
- h. *Minimal significance* — few esteemed attributes, the environment is accommodating to considerable alteration. A region of minimal significance and infrequency at a local level.

The sensitivity levels of the landscape to change and the amount of the landscape effect are combined in Table 1 to ascertain the relevance of the effect on landscape character.

Table 1

		Sensitivity Of Landscape		
		High	Medium	Low
Magnitude of Landscape Effect	High adverse	High adverse significance	High / Medium adverse significance	Medium adverse significance
	Medium adverse	High / Medium adverse significance	Medium adverse significance	Medium / Low adverse significance
	Low adverse	Medium adverse significance	Medium / Low adverse significance	Low adverse significance
	Nil	Neutral significance	Neutral significance	Neutral significance
	Low beneficial	Low beneficial significance	Low beneficial significance	Low beneficial significance
	Medium beneficial	Medium beneficial significance	Medium beneficial significance	Medium beneficial significance
	High beneficial	High beneficial significance	High beneficial significance	High beneficial significance

Evaluation of the visual effect

The extent of visual change can be categorised as high, medium, or low, as well as detrimental or positive, by evaluation of:

- a. alteration or incorporation of essential components of the pre-development perspective;
- b. modification of the overall composition of the broader perspective regarding the fraction of the view occupied by the development,
- c. What proportion of the region will exhibit a noticeable shift in view?
- d. Will the alteration be transient?
- e. To what degree will the scale, massing, layout, and colour of materials differ from the predevelopment perspective?
- f. topography of the location and the adjacent landform
- g. .proximity between the observer and the development.

Significant impact - complete loss or severe modification of essential features of the current landscape, resulting in a markedly atypical and adverse transformation in visual character. The proposal emerges as the predominant element in the picture, relegating other components to a subordinate status.

Moderate size of influence - partial loss or significant alteration to certain components of the current landscape, which may be conspicuous and easily perceived by the viewer, and are atypical in the overall visual character.

Minimal effect magnitude - slight loss or modification of one or more essential components of the landscape/view. The concepts represent a modest aspect of the broader perspective and incorporate aspects that are not atypical within the overall visual character. Knowledge of the plans would not significantly impact the overall quality of the scene.

- No discernible alteration to components within the image or the overall visual aesthetic. The sensitivity of visual receptors can be categorised as high, medium, or low, contingent upon:
the distance from the location, its dimensions, the angle/elevation of the vantage point, contextual factors, meteorological conditions
- The varying individual receptors and the anticipated perspective they provide
The significance of the viewpoint is evaluated based on the number of individuals impacted, its popularity, its appeal to residents and tourists, and its mention in literature, guides, and maps.

Significant perspectives inside a high-quality environment, acknowledged in official maps and guides. In instances where numerous residential properties share a comparable view. Receptors are individuals with a keen interest in their environment who participate in leisure activities related to the aesthetic appreciation of their surroundings.

Moderate significance — perspectives inside a landscape of medium quality. In instances where a limited quantity of residential properties share a comparable perspective. Receptors/individuals possessing a moderate interest in their surroundings while participating in outdoor activities, sports, or recreation.

Minimal significance - perspectives within a subpar landscape. Receptors are individuals with a transient interest in their surroundings, typically while occupied with other activities such as work or travelling through the area on an infrequent basis.

The sensitivity levels of the visual effect and the size of that effect are combined in Table 2 to ascertain visual significance.

The existing Environmental Impact Assessment Regulations (EIA) do not mention solar farms; nonetheless, this should not be a basis for concluding that an EIA is unnecessary. Upon reviewing the EIA Regulations, a comparison may be established between solar panels and the subsequent two categories of development:

- Glasshouses, which also modify land cover across potentially extensive areas, are associated with considerable landscape and visual impacts. “Development, such as greenhouses, on previously uncultivated land is unlikely to necessitate an Environmental Impact Assessment (EIA) unless it exceeds 5 hectares.” EIA circular
- Industrial facilities for power generation - where the development area exceeds 0.5 hectares, with visual impact being a primary concern.

Table 2. sensitivity levels of the visual effect and the size of that effect

		Sensitivity Of Receptor		
Magnitude of Visual Effect	High adverse	High adverse significance	Medium adverse significance	Low adverse significance
	Medium adverse	High / Medium adverse significance	Medium adverse significance	Medium / Low adverse significance
	Low adverse	Medium adverse significance	Medium / Low adverse significance	Low adverse significance
	Nil	Neutral significance	Neutral significance	Neutral significance
	Low beneficial	Low beneficial significance	Low beneficial significance	Low beneficial significance
	Medium beneficial	Medium beneficial significance	Medium beneficial significance	Medium beneficial significance
	High beneficial	High beneficial significance	High beneficial significance	High beneficial significance

The impact of the plan on landscape character and visual amenity must be assessed through a full Landscape and Visual Impact analysis, regardless of the applicability of the EIA Regulations to the application.

Evaluation.

This assessment must encompass the following details:

- Overview of the evolution
- The necessity for the establishment of a set within local, regional, and national strategies;
- The timeline for building, operation, and decommissioning;
- The site's geographical position and general configuration;
- .Design and specifications of solar panels, construction and installation methods;
- Prudent assessments of the volume and nature of traffic anticipated during development

and operation.

Overview of the Site

- a. an exposition of the primary rationale for site selection and any alternative designs or layouts that have been contemplated.
- b. Designated area for the installation of panels, explicitly delineated and represented on a map or plan;
- c. Depiction of the land utilisation in the adjacent region;
- d. A description of the policies, plans, and designations pertinent to the proposal;
- e. Assessment of the direct, indirect, secondary, and cumulative effects, both short-term, medium-term, and long-term, arising from the presence of the development.

Preliminary Landscape Conditions

- a. The present state of the terrain;
- b. Local Authorities Landscape Character Assessment will furnish the foundational landscape character information, augmented by a study to evaluate the specific effects of the development.
- c. The site's relationship to designated landscape areas at national, regional, or local levels, as well as to areas of landscape significance or aesthetic quality.
- d. A comprehensive account of all foundational data sources and the methodologies employed to augment this information;
- e. The landscape baseline must be assessed about its sensitivity and significance. The sensitivity assessment of each landscape element must correspond to its quality value, its contribution to landscape character, and the extent to which the specific element or characteristic can be changed or substituted.

Projections of Consequences

- a. Evaluate the extent of alteration to the landscape and visual components as a divergence from the baseline conditions for each phase of the proposal. Attention must be paid to tourist and resident demographics, as well as seasonal fluctuations;
- b. Generate a Zone of Theoretical Visibility (ZTV) diagram for the development, delineating at least 1km, 2km, and 4km radii from the site.
- c. The techniques employed to determine the magnitude must be explicitly articulated and deemed suitable and rational for the significance of the landscape and visual impact;
- d. Assumptions or unsupported data utilised in the projections must be identified and accompanied by an assessment of the dependability or confidence in those assumptions or data.
- e. Assessment of the direct, indirect, secondary, and cumulative consequences, both short-term and long-term, arising from the development's existence.

Significance of Impact

- a. Explicitly delineate the assessments that provide the basis for the allocation of significance;
- b. The evaluation of importance must take into account the impact's divergence from the defined landscape baseline state, the sensitivity of the landscape and receptors, and the degree to which the impact can be mitigated or is reversible.
- c. The array of factors likely to affect the evaluation of significance should be distinctly delineated;
- d. Elucidate how these variables will influence the importance of the affects during the development's lifespan;
- e. Determine the importance of residual repercussions after mitigation efforts.

Reduction of severity

- a. Outline the strategies suggested to prevent, mitigate, and, if feasible, rectify substantial negative effects on landscape character and visual amenity;
- b. Assess the efficacy of the specified measures;
- c. Explicit delineation of the implementation of mitigation measures.

Presentation of the Landscape and Visual Impact Evaluation

- a. The paper must exhibit clarity and logical organisation in its layout and presentation, ensuring comprehensibility for a non-specialist audience.
- b. The document must present a balanced, impartial assessment of the landscape and visual impacts, supported by reasoned and justifiable reasoning.
- c. A comprehensive lexicon of all technical terms and a complete reference list must be included;
- d. Plans, diagrams, and visual representations must be supplied to facilitate comprehension of the development and its effects, and should be precisely identified with all locations referenced in the text.

Non-Technical Overview

- a. A self-contained document designed for a non-expert audience, facilitating comprehension of the proposal's geography and visual effects;
- b. To provide a comprehensive description of the development, the landscape character and visual amenity features likely to be considerably impacted, the anticipated significant effects, and the mitigation actions to be enacted;
- c. At a minimum, incorporate plans, maps, and other visual representations that depict the application site's location, the development's footprint, and the positioning of essential components.

Appendix B:

Electricity Generation Capacity

Planning applications for commercial-scale solar development must include the following information. Although the National Planning Policy Framework indicates that local authorities should not mandate applicants for energy developments to demonstrate the overall necessity for renewable or low carbon energy, and acknowledges that small-scale projects significantly contribute to reducing greenhouse gas emissions, this is regarded as pertinent background information.

Observations:

- a. Installed capacity refers to the maximum continuous output rating of generating equipment under conditions specified by the manufacturer. This refers to the power produced when the machine operates at maximum capacity.
- b. The capacity factor is a calculated metric that compares a facility's actual production over a certain period with the theoretical output had the plant operated at full capacity throughout that time frame. The capacity factor must consider the particular equipment and the specific site. It is articulated as a percentage.
- c. Projected yearly power generation based on installed capacity and capacity factor.
- d. The quantity of residential properties that could be supplied with energy based on the projected annual output,

Appendix C:

Overview of EIA Screening Procedures

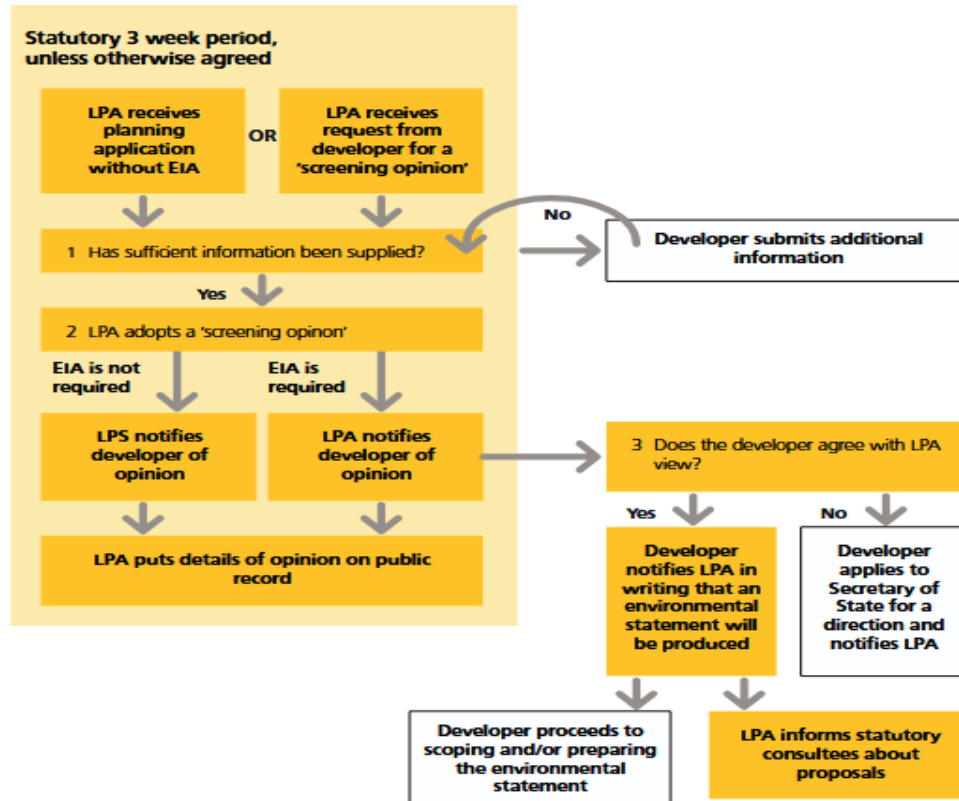


Figure 3. Flow chart 1: Screening procedures overview

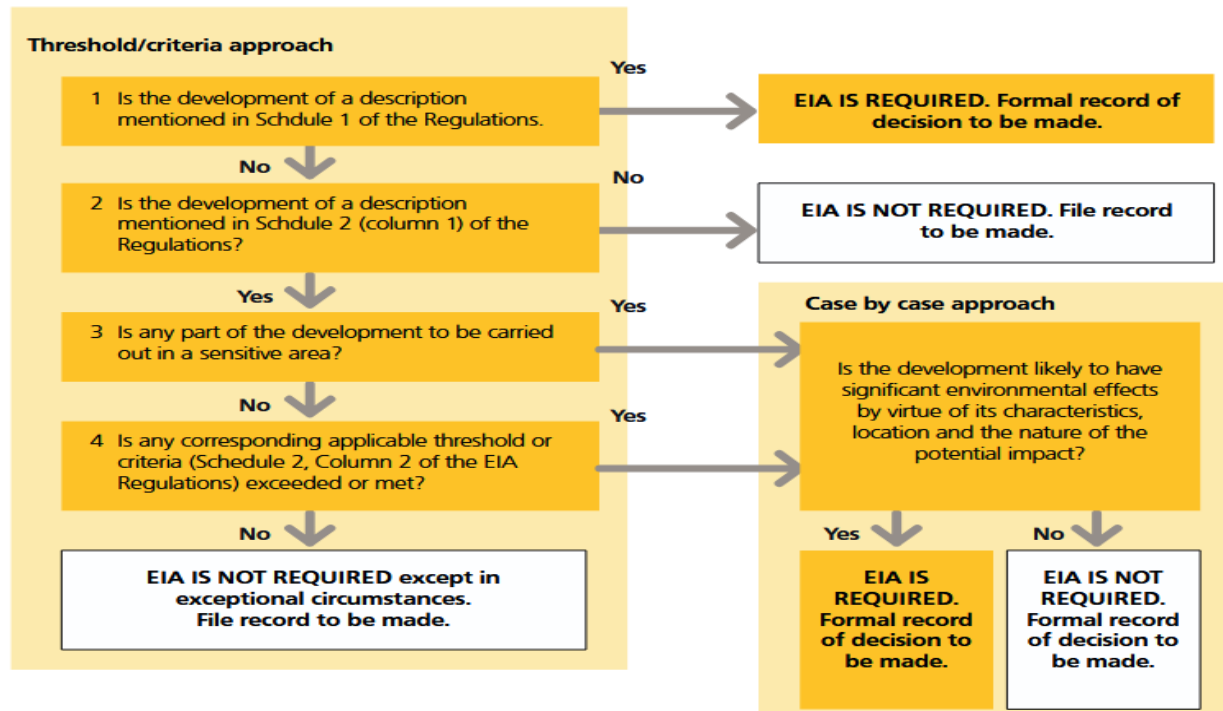


Figure 4. Flow chart 2: The screening decision



A SYSTEMATIC REVIEW OF COLLABORATION BETWEEN TERTIARY INSTITUTIONS AND INDUSTRY

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ABSTRACT

The partnership between higher education institutions and industry is increasingly regarded as a means to foster innovation through the exchange of information. This is demonstrated by a substantial rise in research examining the subject from many viewpoints. This collection of information remains scattered and lacks a cohesive overview. To rectify this deficiency, we implemented a systematic approach to examine the literature on Tertiary Institution-industry collaboration (TIIC). The review identified five fundamental features that supported the hypothesis of TIIC. We incorporate these essential elements into a comprehensive process framework, which, along with the review, significantly contributes by producing an integrated analysis of the literature regarding this phenomenon. Multiple research directions are identified as derived from the study.

1. INTRODUCTION

Tertiary institutions—industry collaboration (TIIC) denotes the interaction between components of the higher education system and industry, primarily aimed at fostering the interchange of knowledge and technology (Bekkers & Bodas Freitas, 2008; Siegel, Waldman, & Link, 2003). TIIC has a lengthy history (Bower, 1993; Oliver, 2004) as a method for enhancing organisations' knowledge repositories (Cricelli & Grimaldi, 2010). Recently, there has been a significant rise in these collaborations across various countries, including the United States (e.g., Lehrer, Nell, & Garber, 2009), Japan (e.g., Woolgar, 2007), Singapore (e.g., Lee & Win, 2004), and European Union nations (e.g., Barrett, Austin, & McCarthy, 2000; Gertner, Roberts, & Charles, 2011; Powers, 2003). This rise has been ascribed to a confluence of forces affecting both the industrial sector and higher education institutions (Giuliani & Arza, 2009; Meyer-Krahmer & Schmoch, 1998). Industries have faced pressures such as rapid technical advancements, abbreviated product life cycles, and fierce worldwide competition, which have

fundamentally altered the competitive landscape for most companies (Bettis & Hitt, 1995; Wright, Clarysse, Lockett, & Knockaert, 2008). Tertiary institutions face pressures from the expansion of new knowledge and the challenges of escalating costs and funding issues, which impose significant resource demands on them to establish partnerships with firms to maintain their competitive edge across all disciplines (Hagen, 2002). Furthermore, there is increasing societal pressure on higher education institutions to be perceived primarily as drivers of economic growth, rather than as entities performing their historical broader social responsibilities, such as education and knowledge generation (Blumenthal, 2003; Philbin, 2008). The demands on both parties have generated a growing impetus for the development of TIICs, which seek to bolster innovation and economic competitiveness at institutional levels (e.g., countries and sectors) through information exchange between academic and commercial sectors (Perkmann et al., 2013). Furthermore, TIIC is widely regarded as an effective mechanism for augmenting organisational capacity in open innovation, wherein an organisation utilises external networks to foster innovation and knowledge (Dess & Shaw, 2001), serving as a supplementary alternative to conventional internal R&D (Harvey & Tether, 2003).

Although there has been an increase in TIIC-related research, the existing literature remains fragmented and lacks a holistic perspective (Bovaird, 2007; Perkmann et al., 2013). The objective of this study is to enhance comprehension of TIIC for knowledge and technology transfer by systematically reviewing and critically integrating the key elements of this inter-organizational interaction. Our assessment method was specifically directed by a principal research question: What are the predominant topics of TIIC? We integrate our findings by amalgamating several independently conducted investigations, perhaps with contradictory results, and synthesising their outcomes in particular domains. We contribute to the literature and practice in three distinct ways. Initially, we provide a thorough systematic assessment of the current understanding of TIIC. This enabled us to discern five major elements that prevail in the TIIC literature. This extensive coverage in a single study seems to be unprecedented in the literature, as the majority of prior research has focused on only one or two of these domains simultaneously, such as proposing a typology for TIIC (Dess & Shaw, 2001), identifying characteristics of firms and tertiary institutions involved in TIIC (Agrawal, 2001), and examining the antecedents and consequences of TIIC (Perkmann et al., 2013). Furthermore, our research, unlike other studies (e.g., Philbin, 2008), examines TIIC in its whole rather than solely concentrating on 'contract research' TIIC. The former presents a broader viewpoint for TIIC, suggesting a bi-directional exchange of knowledge, whereas the latter typically involves a unidirectional transfer of knowledge from higher education institutions, primarily concentrating on technological commercialisation (Meyer-Krahmer & Schmoch, 1998). This study is unique compared to prior research as it equally emphasises both higher education institutions and industry viewpoints. Dependence on information obtained from a singular perspective typically undermines the validity of results and constrains the opportunity to attain a holistic understanding of TIIC (Santoro & Chakrabarti, 2002). Secondly, we consolidate our findings into a conceptual process framework that connects the five predominant topics in the TIIC literature. The framework was utilised to identify potential deficiencies in our understanding of this occurrence and provide various directions for further research. The study is pertinent to practical applications. We offer additional insights into the diverse methods of technology exchange between higher education institutions and industry, namely through the established process framework, enabling partnering organisations to focus more on the associated activities.

The remainder of this work is structured as follows. The subsequent section delineates the methodological framework for the systematic review. We summarise the review outcomes in five principal areas, termed TIIC core themes: forms, motives, formation and activities, enablers and inhibitors, and outcomes. The fourth section critically examines the prevailing theories supporting TIIC and utilises the review findings to create a conceptual process framework for TIIC. The final portion presents the conclusion and fresh research directions.

2. METHODOLOGICAL FRAMEWORK FOR THE SYSTEMATIC LITERATURE REVIEW

Systematic literature reviews, initially developed in medical research (Black, 2001), are now being utilised in the social sciences (Burrows, 2000) and management (Pittaway & Cope, 2007; Shwom, 2014). A systematic review is an investigation designed to address a well-defined subject by locating, delineating, and assessing evidence from all published research pertinent to that question within specified parameters (Eriksson, 2013). Significantly, it diverges from conventional narrative reviews by employing a systematic and rigorous methodology that mitigates subjective bias and diminishes the likelihood of neglecting pertinent literature. A systematic review can be distinguished from conventional literature reviews in that traditional reviews frequently lack an effort to derive generalisations or cumulative knowledge from the material examined (Davies, 2000). The objective is to ascertain the scope and variety of existing literature, much of which may be inconclusive, and to identify a gap that new research could address (Tranfield, Denyer, & Smart, 2003). Davies (2000) characterises such evaluations as opportunistic, selective, and haphazard, lacking a systematic and comprehensive examination of all pertinent material.

The primary purpose of this study was to ascertain the key components of TIIC and to investigate their interrelations to facilitate conceptual advancement in TIIC literature. This objective was shaped by our observation of the substantial body of research on Tertiary institution-Industry Collaboration (TIIC), which has produced extensive literature highlighting the mechanisms, including initial conditions, established for the interaction between higher education institutions and industry, along with the outcomes of such partnerships. A systematic review of the existing literature in this domain was deemed essential to evaluate current knowledge and consolidate disparate findings, thereby presenting them in a manner that is more pertinent, reliable, and offers collective insights and guidance for academics, practitioners, and decision-makers.

In accordance with this purpose, we predominantly adhered to the methodology proposed by Tranfield et al. (2003) to conduct the review. We commenced by identifying all pertinent articles published between 1990 and 2014. Literature published before 1990 was excluded due to the perception that collaboration between higher education institutions and industry was deemed less significant during that age (Howells & Nedeva, 2003; Poyago-Theotoky, Beath, & Siegel, 2002). Furthermore, given that the phenomena of TIIC is dynamic (Blumenthal, 2003; Newberg & Dunn, 2002), the cumulative aspect of the discipline ensures that the risk of neglecting significant earlier contributions will be alleviated by contemporary studies that expand upon prior discoveries. The search approach exclusively encompassed peer-reviewed journal papers available in electronic databases, since they possess greater authenticity and are more likely to address the primary contributions in the field (Payne, Moore, Griffis, & Autry, 2011; Perkmann, Neely, & Walsh, 2011). A search was performed in the following electronic databases for titles and abstracts of potentially pertinent studies: ABI Global, Applied Social Sciences Index and Abstracts, Elsevier (Science Direct), International Bibliography of the Social Sciences, Ingenta, NetEc, and Social Science Citation Index (Web of Science). These

specific databases have been chosen due to their extensive coverage of the literature in the relevant field of study. No limitations were imposed regarding the nation of origin, source sector (such as academic, governmental, policy, etc.), or industrial type. Only published works in the English language were included. We examined these databases to identify pertinent studies by employing specific combinations of terms, including: 'tertiary institution' OR 'academia' OR 'higher educational institution' AND 'business' OR 'industry' OR 'firm' AND one of the following: 'alliance', 'bridge', 'collaboration', 'cooperation', 'exploitation', 'innovation', 'inter-organizational relationship', 'interaction', 'link', 'partnership', 'research and development', 'relationship', 'technology transfer', 'knowledge transfer', and 'scheme'. While the use of these terms was anticipated to initially produce a substantial volume of studies, it was essential to guarantee that all possibly pertinent studies were taken into account. This approach produced over 1500 results, deemed our preliminary sample.

Considering that the primary focus of the review is to thoroughly delineate the essential elements of TIIC, we examined the titles and abstracts (and, in some instances, the introductions) of each article to ascertain their principal objectives and contributions (Payne et al., 2011; Shwom, 2014). This stage was crucial for establishing the inclusion and exclusion criteria subsequently utilised to pick our final sample. Multiple preliminary coding themes have evolved inductively. Following extensive deliberations among the research team, five predominant facets of TIIC have been established: forms, motives, formation and operationalisation, facilitators and inhibitors, and outcomes. Based on these factors, we established six questions to serve as criteria for the inclusion and exclusion of research in the review to ascertain the final sample. The following questions are delineated below:

1. Does the study examine the collaboration between tertiary institutions and industry for technology transfer as a primary focus?
2. Does the study examine TIIC motivations?
3. Does the study analyse TIIC forms?
4. Does the study offer insights into the creation and operationalisation of TIIC?
5. Does the study encompass elements that promote or hinder TIIC?
6. Does the study address the results (advantages or disadvantages) of TIIC?

A study was incorporated in the final evaluation if the response to question 1 and at least one of the subsequent questions (2, 3, 4, 5, or 6) was affirmative (i.e., Yes). The screening process included, in addition to the aforementioned questions, a quality evaluation check. A quality evaluation was conducted to differentiate between higher and lower quality studies within the existing evidence base. Quality assessment was essential to evaluate a study's internal validity and the extent to which its design, execution, and analysis have mitigated biases or inaccuracies. The evaluation was based on the content of each study, adhering to a method proposed by Tranfield et al. (2003). The evaluation was facilitated using Farrington's methodological quality scale (Farrington, 2003). the fifth criterion, external validity (which pertains to the generalisability of the study findings beyond the specific context in which the research was conducted).

External validity for quantitative studies and representativeness/triangulation for qualitative analysis. Each study was evaluated and categorised as either "Quality Acceptable" or "Quality Unacceptable," with only those designated as "Quality Acceptable" included in the review. Through the application of inclusion and exclusion criteria, along with quality assessments, the final sample consisted of 109 studies, detailed in Appendix A.

Subsequent to this phase, we used methodologies from qualitative data analysis, specifically the matrix approach and tabulation methodology (Miles & Huberman, 2008), on the complete texts of the ultimately selected publications. This sought to gather facts and information specifically pertaining to the five highlighted critical features. We commenced the coding process by meticulously examining each article, word by word, to identify segments of text and associate them with pertinent major themes (i.e., the fundamental components). The subsequent process involved evaluating the content of each subject, which has been generated as an individual paper or a summary for each important theme. Subsequently, we progressed to the second and third levels of coding by aggregating pertinent information segments under designated titles, which subsequently form the sub-themes associated with each core topic. Furthermore, meticulous attention has been devoted at this stage to analysing and emphasising the divergence and convergence among the various papers, while seeking explanations for any discrepancies. This sought to enhance comprehension of the essence of these essential concepts and their significance to the TIIC subject.

Although the systematic review process demonstrates superior transparency and receptiveness to critique compared to conventional narrative review approaches, it possesses several drawbacks (Hakala, 2011). The initial concern pertains to the parameters of the investigation. The present research analyses and discusses papers published in academic journals from 1990 to 2014. This suggests the possibility of omitting certain pertinent studies (e.g., book chapters) from the review. Nevertheless, this is a permissible technique in systematic reviews (Pittaway & Cope, 2007), as significant contributions in a certain study domain typically manifest consistently in subsequent journal publications. The second limitation pertains to the selection of keywords utilised to regulate the inclusion criterion of the articles. To alleviate the repercussions of this issue, a meticulous three-step review process has been implemented, encompassing the title, abstract, and complete content. This would guarantee that all pertinent studies have been reviewed.

3. RESULTS

This section presents the findings from the systematic review as a response to a specific question. Each question pertains to one of the five predominant themes identified in the investigation.

3.1 What are the organisational structures of TIIC?

The predominant types of TIIC examined in practice and literature include Joint Ventures, Networks, Consortia, and Alliances (Barringer & Harrison, 2000), with variations in the extent of participant interconnection. Nevertheless, authors disagree on the definitions and distinctions of the various kinds of TIIC (Bruneel, D'esteb, & Salter, 2010).

The aforementioned items aligned with the conclusions from the review. Although TIIC seems to include all types of relationships between higher institutions and industry, several additional forms were identified (see Table 1), suggesting that the potential for interaction within TIIC is quite extensive (Shenhar, 1993). Various researchers proposed distinct typologies or taxonomies of the relationships. Chen (1994) categorised the types of TIIC for technology exchange based on the relationship duration and the technology transfer. Santoro and Gopalakrishnan (2000) propose four classifications for Tertiary institution-Industry Collaborations (TIICs): (1) research support (e.g., Endowment/Trust Fund), (2) cooperative research (e.g., institutional agreements, group arrangements, institutional facilities, informal intentions), (3) knowledge transfer (e.g., recruitment of recent graduates, personal interactions, institutional programs, cooperative education), and (4) technology transfer (e.g., product development and commercialisation activities via tertiary institution research centres).

The review thus validated Blackman and Seagal's (1991) assertion that developing a typology illustrating all potential connections between academic institutions and industry is exceedingly challenging. The framework developed by Bonarccorsi and Piccaluga (1994) was deemed sufficiently comprehensive and appropriate for this investigation. The framework had six primary elements as delineated in Table 1: Personal Informal Relationships, Personal Relationships, Third Party, Formal Targeted Agreements, Formal Non-targeted Agreements, and Creation of Focused Structures. The initial classification by Bonarccorsi and Piccaluga (1994) has been expanded to incorporate more information from the systematic review, as illustrated in Table 1. The six groups demonstrate a progressive level of organisational engagement, which can be succinctly examined across three dimensions: (a) involvement of organisational resources from the tertiary institution; (b) duration of the agreement; and (c) extent of formalisation. In the first dimension, the tertiary institution does not use organisational resources if the firm's interaction is solely with an academic individual, absent a formal agreement with the institution. The involvement of postsecondary institutions in resources escalates from Formal Personal Relationships to Focused Structures, wherein the entire institution engages in specialised frameworks for collaboration with industry. The duration of the agreement between tertiary institutions and enterprises, as the second dimension, may range from brief (yet renewable) in the context of Personal Formal Relationships, to extended in the case of specialised or Focused Structures. Exceptions arise in interactions between tertiary institutions and industries facilitated by a Third Party, which may result in prolonged agreements if the relationship becomes more stable. Upon formalising the agreement, the third dimension is either minimal or entirely lacking in Personal Informal Relationships. In Personal Formal Relationships and Third Parties, the agreement may or may not be formalised, but in other categories, the relationships are formalised (Bonarccorsi & Piccaluga, 1994). Ring and van de Ven (1994) emphasise that the matter of formalisation is crucial, as heightened formalisation and oversight of the relationship in a TIIC may incite conflict and distrust among the parties striving to preserve their organisational autonomy amidst growing interdependence.

1994; Santoro and Gopalakrishnan, 2000.

3.2 What are the motivations behind TIIC?

To examine the motivations for TIIC, we reference Oliver's (1990) framework, which identified six essential conditions as universal determinants of inter-organizational relationships. These contingencies might be viewed as foundational to organisations' desire for interaction. Oliver observed that while each determinant independently suffices to initiate a relationship, these variables may also interact or coexist when organisations opt to establish an inter-organizational relationship. According to Oliver, two fundamental assumptions underpin these determinants. Initially, organisations are presumed to intentionally decide to create an Inter-Organizational Relationship (IOR) for well-defined objectives. Secondly, an organisational perspective from top management is presumed, however the determinants may also elucidate lower-level and sub-unit factors (Oliver, 1990). Conversely, the six scenarios appeared to align closely with strategic motivations for partnerships (Kyrgidou & Spyropoulou, 2013). Furthermore, the systematic research revealed that the motivations of higher institutions and industry involved in TIICs strongly correspond with the six essential variables or factors outlined by Oliver (1990). Consequently, these contingencies were employed to classify the motivations for TIICs identified in the investigations. While several motivations may pertain to multiple determinants, they have been categorised under the determinant deemed most suitable. Furthermore, as the reasons for higher institutions to engage in Tertiary Institutions-Industry Collaborations (TIICs) differ in certain aspects from those of industry, the motives for both entities are examined independently.

Table 2. Motivations for Tertiary institutions and industry: a comparison.

Relationships and agreements		Results
Personal Relationships	Informal	– Academic spin-offs – Individual consultancy (paid for or free) – Information exchange forums – Collegial interchange, conference, and publications – Joint or individual lectures – Personal contact with tertiary institution academic staff or industrial staff – Co-locational arrangement
Personal Relationships	Formal	– Student internships and sandwich courses – Students' involvement in industrial projects – Scholarships, Studentships, Fellowships and postgraduate linkages – Joint supervision of PhDs and Masters theses – Exchange programmes (e.g. secondment) – Sabbaticals periods for professors – Hiring of graduate students – Employment of relevant scientists by industry – Use of tertiary institution or industrial facility (e.g., lab, database, etc.)
Third Party		– Institutional consultancy (tertiary institution companies including Faculty Consulting) – Liaison offices (in tertiary institutions or industry) – General Assistance Units (including technology transfer organizations) – Government Agencies (including regional technology transfer networks) – Industrial associations (functioning as brokers) – Technological Brokerage Companies
Formal Agreements	Targeted	– Contract research (including technical services contract) – Patenting and Licensing Agreements (licensing of intellectual property rights) – Cooperative research projects – Equity holding in companies by tertiary institutions or faculty members – Exchange of research materials or Joint curriculum development: – Joint research programmes (including Joint venture research project with a tertiary institution as a research partner or Joint venture research project with a tertiary institution as a subcontractor) – Training Programmes for employees
Formal Targeted Agreements	Non-	– Broad agreements for U-I collaborations – Endowed Chairs and Advisory Boards – Funding of tertiary institution posts – Industrially sponsored R&D in tertiary institution departments – Research grant, gifts, endowment, trusts donations (financial or equipment), general or directed to specific departments or academics
Focused Structures		– Association contracts – Innovation/incubation centers – Research, science and technology parks – Tertiary institution—Industry Consortia – Tertiary institution—Industry research cooperative research centers – Subsidiary ownerships – Mergers

Table 1. Organizational forms of TIIC

Relationships and agreements		– Results
Personal Relationships	Informal	– Academic spin-offs – Individual consultancy (paid for or free) – Information exchange forums – Collegial interchange, conference, and publications – <i>Joint or individual lectures</i> – <i>Personal contact with tertiary institution academic staff or industrial staff</i> – <i>Co-locational arrangement</i>
Personal Relationships	Formal	– Student internships and sandwich courses – <i>Students' involvement in industrial projects</i> – Scholarships, Studentships, Fellowships and postgraduate linkages – <i>Joint supervision of PhDs and Masters theses</i> – Exchange programmes (e.g. secondment) – Sabbaticals periods for professors – <i>Hiring of graduate students</i> – <i>Employment of relevant scientists by industry</i> – <i>Use of tertiary institution or industrial facility (e.g., lab, database, etc.)</i>
Third Party		– Institutional consultancy (tertiary institution companies including Faculty Consulting) – Liaison offices (in tertiary institutions or industry) – <i>General Assistance Units (including technology transfer organizations)</i> – Government Agencies (including regional technology transfer networks) – Industrial associations (functioning as brokers) – <i>Technological Brokerage Companies</i>
Formal Agreements	Targeted	– Contract research (including technical services contract) – <i>Patenting and Licensing Agreements (licensing of intellectual property rights)</i> – Cooperative research projects – <i>Equity holding in companies by tertiary institutions or faculty members</i> – Exchange of research materials or Joint curriculum development: – <i>Joint research programmes (including Joint venture research project with a tertiary institution as a research partner or Joint venture research project with a tertiary institution as a subcontractor)</i> – Training Programmes for employees
Formal Targeted Agreements	Non-Targeted	– Broad agreements for U-I collaborations – <i>Endowed Chairs and Advisory Boards</i> – <i>Funding of tertiary institution posts</i> – <i>Industrially sponsored R&D in tertiary institution departments</i> – Research grant, gifts, endowment, trusts donations (financial or equipment), general or directed to specific departments or academics
Focused Structures		– Association contracts – Innovation/incubation centers – Research, science and technology parks – Tertiary institution—Industry Consortia – Tertiary institution—Industry research cooperative research centers – <i>Subsidiary ownerships</i> – Mergers

The *italic* indicates new organizational forms as identified from the review.

Table 2. Motivations for Tertiary Institutions and industry: a comparison

	Tertiary Institutions	Industry
Necessity	– Responsiveness to government policy – Strategic institutional policy	– Responsiveness to government initiatives/policy – Strategic Institutional policy
Reciprocity		– Access to students for summer internship or hiring – Hiring of faculty members
Efficiency	– Access complementary expertise, state-of-the-art equipment and facilities – Employment opportunities for tertiary institution graduates – Access funding for research (Government grant for research & Industrial funding for research assistance, lab equipment, etc.) – Business opportunity, e.g. exploitation of research capabilities and results or deployment of IPR to obtain patents – Personal financial gain for academics	– Commercialize tertiary institution-based technologies for financial gain – Benefit financially from serendipitous research results – Cost savings (easier and cheaper than to obtain a license to exploit foreign technology) – National incentives for developing such relations such as tax exemptions and grants – Enhance the technological capacity and economic competitiveness of firms – Shortening product life cycle – Human capital development
Stability	– Responsiveness to government policy – Strategic institutional policy – Access complementary expertise, state-of-the-art equipment and facilities – Employment opportunities for tertiary institution graduates – Access funding for research (Government grant for research & Industrial funding for research assistance, lab equipment, etc.) – Business opportunity, e.g. exploitation of research capabilities and results or deployment of IPR to obtain patents – –	– Shift in knowledge-based economy (growth in new knowledge) – Business growth – Access new knowledge, cutting-edge technology, state-of-the art expertise/research facilities and complementary know-how – Multidisciplinary character of leading-edge technologies – Access to research networks or pre-cursor to other collaborations – Solutions to specific problems – Subcontract R&D (for example due to lack of in- house R&D) – Risk reduction or sharing –
Legitimacy	– Personal financial gain for academics – Shift in knowledge-based economy (growth in new knowledge) – Discover new knowledge/test application of theory – Obtain better insights into curricula development – Expose students and faculty to practical problems/ applied technologies – Publication of papers – Shift in knowledge-based economy (growth in new	– Enhancement of corporate image – Maintain control over proprietary technology

	knowledge)	
	– Discover new knowledge/test application of theory	
	– Obtain better insights into curricula development	
	– Expose students and faculty to practical problems/ applied technologies	
	– Publication of papers	
	– Societal pressure	
	– Service to the industrial community/society	
	– Promote innovation (through technology exchange)	
	– Contribute to regional or national economy	
	– Academics’ quest for recognition or achieve eminence	
	–	
Asymmetry	– NA	— Maintain control over proprietary technology

3.3 Perspective of tertiary institutions

The investigation indicates that the motives for tertiary institutions to engage with industry are summarised in Table 2. Nevertheless, none of the reasons discovered for higher education institutions could be classified under the determinant. The asymmetry indicates that tertiary institutions are not motivated to engage in partnerships with industry to exert power or control over its resources.

Essentiality. In the context of escalating global competition and swift technological advancements, governments are promoting partnerships between higher education institutions and industry to enhance innovation efficiency and subsequently increase wealth creation (Barnes, Pashby, & Gibbons, 2002). Hall, Link, and Scott (2001) and López-Martínez, Medellín, Scanlon, and Solleiro (1994) assert that a critical concern for policymakers and research budget stakeholders, such as Research Councils, is the efficacy of the interface between higher education institutions and industry. This interface is essential for the prompt and effective transfer of applicable research to industry, thereby fostering economic growth and well-being. Consequently, tertiary institutions are progressively focussing on promoting Tertiary institution-Industry Collaboration (TIIC) in alignment with government policy and as part of their institutional strategic initiatives (Howells, Nevada, & Georghiou, 1998; Perkmann, King, & Pavelin, 2011a).

Mutual exchange. Sherwood, Butts, and Kacar (2004) contend that higher education institutions provide substantial access to diverse research expertise and infrastructure, while industry grants significant access to expertise in product development and commercialisation, market knowledge (Sherwood et al., 2004), and employment opportunities for graduates of tertiary institutions (Lee & Win, 2004; Santoro & Betts, 2002). Consequently, postsecondary institutions may be incentivised to establish partnerships with industry to leverage these assets for reciprocal benefit.

Effectiveness. Government grants facilitate new TIIC initiatives (Harman & Sherwell, 2002); however, the mounting pressures on public funding for tertiary institutions have strongly

incentivised these institutions to pursue alternative revenue sources for fundamental research and equipment. This includes the commercialisation of faculty research and the exploitation of intellectual property rights or patent licensing, aimed at diminishing their reliance on public funding (Logar, Ponzurick, Spears, & France, 2001). Blumenthal (2003) and Santoro and Gopalakrishnan (2001) indicate that connections with industry are attractive to tertiary institutions due to the reduced bureaucratic constraints associated with sector funding compared to public support. Other scholars, like Siegel, Waldman, Atwater, and Link (2004), have asserted that faculty members may be incentivised by personal financial benefit to engage in connections with industry.

Equilibrium. Collaboration theory posits that inter-organizational relationships serve as a technique to be employed when the environment becomes significantly unstable and unpredictable (Boddy, Macbeth, & Wagner, 2000; Grey & Wood, 1991). Oliver (1990) posits that organisations are driven by the stability contingency to engage in collaboration, thereby addressing environmental uncertainty to attain predictability and reliability. The review identified motivations connected to this contingency, including the transition to the contemporary knowledge-based economy, which has transformed TIIC from sponsorship to partnership, emphasising continuous engagement, as stated by Jacob, Hellstrom, Adler, and Norrgren (2000). The expansion of new knowledge has imposed significant resource demands on individual tertiary institutions, prompting them to form alliances with industry to maintain a competitive advantage across all disciplines. Cyert and Goodman (1997) assert that scientists in tertiary institutions generally perceive these connections as conducive to the development and testing of hypotheses, refinement of their skills, and the training and placement of their students. Meyer-Krahmer and Schmoch (1998) and Santoro and Chakrabarti (2001) have asserted that higher education institutions partner with industry to immerse academics and students in industrial settings, providing access to the latest findings from industrial research, instructional case studies, and practical challenges via projects. All of these factors contribute to curriculum creation and enhance the quality of instruction (Santoro & Gopalakrishnan, 2000). Moreover, Harman and Sherwell (2002) propose that a significant motivation for higher education institutions to collaborate with industry is the opportunity for publication in academic journals, as generating publicly accessible information would underscore the fundamental mission of these institutions in knowledge dissemination (Newberg & Dunn, 2002).

Legitimacy. Another impetus for higher education institutions to forge partnerships with industry is an inherent aspiration to elevate their prestige (Mora-Valentin, 2000). There is an increasing societal (political and public) demand for tertiary institutions to exhibit enhanced social accountability, entrepreneurship, and overall economic significance to society (Cohen, Florida, Randazzese, & Walsh, 1998). This demand compels tertiary institutions to engage in collaborative efforts with industry through the exchange or dissemination of knowledge and technology (Siegel, Waldman, & Link, 2003), thereby facilitating their contribution to economic development (Blumenthal, 2003; Hagen, 2002). Siegel et al. (2004) noted that a key motivation for scientists in tertiary institutions is recognition within the industrial scientific world, which generally arises from collaborative publications, presentations at esteemed conferences, and research funding. Moreover, industrial sponsorship facilitates professors in undertaking research that enables them to attain academic distinction.

3.4 Sector viewpoint

The industry's incentives for engaging with postsecondary institutions encompassed all six of Oliver's contingencies, as detailed in Table 2.

Essentiality. Governments have been necessitated by swift global transformations in the competitive and technological landscape to implement measures that foster research collaboration between the two sectors, as they contend that tertiary institutions can contribute to economic revitalisation if they share their knowledge and expertise through industry-linked partnerships (Mora-Valentin, 2000; Perkmann et al., 2013). Consequently, numerous regional and national research initiatives have been established by governments (Caloghirou, Tsakanikas, & Vonortas, 2001), including the UK Knowledge Transfer Partnerships. For industry to derive maximum value from these programs, collaboration with tertiary institutions is essential (Howells et al., 1998).

Imbalance. An impetus for industry to engage in tertiary institution-industry collaboration (TIIC) is the pursuit of commercialising technology developed by tertiary institutions for profit (Siegel, Waldman, & Link, 2003). Consequently, numerous corporations seek exclusive rights to the developed technologies. Consequently, they are apprehensive about preserving authority over the trajectory of research at higher education institutions (Newberg & Dunn, 2002) and retaining proprietary control over the technology.

Mutual exchange. Another impetus for industry to engage in TIICs is to obtain access to students for summer internships or recruitment (Ankrah, Burgess, Grimshaw, & Shaw, 2013; Siegel, Waldman, & Link, 2003). Most TIIC research programs aim to recruit the most qualified students due to the interaction (Fellera, Ailesb, & Roessnerb, 2002). Faculty members or senior researchers may also be engaged as consultants during their permitted external work hours (Perkmann, King, et al., 2011).

Effectiveness. From an efficiency perspective, there are multiple incentives for industries to engage in TIICs with higher education institutions. Cohen et al. (1998) assert that higher education institutions and industrial research can improve enterprises' sales, research and development productivity, and patenting endeavours. Companies collaborate with higher education institutions to potentially gain financially from unexpected outcomes of research endeavours, innovative products, and cost efficiencies, particularly in knowledge generation and utilisation (George, Zahra, & Wood, 2002), all of which can confer a competitive edge and enhance financial performance (Grant, 1996). Another motive is the encouragement of research and development (R&D) and technological advancement by governments through financial instruments such as grants and tax credits, alongside the establishment of a legal framework that supports R&D (Barnes et al., 2002). Furthermore, the advancement of human capital, encompassing ongoing professional education (Santoro & Chakrabarti, 1999), access to innovative technologies with a multidisciplinary approach, and state-of-the-art research facilities, constitutes industry incentives, as these factors alleviate the effects of diminishing product life cycles (PLC) and consequently bolster competitive advantage (Bonaccorsi & Piccaluga, 1994). TIIC provides firms access to a plethora of innovative competitive technologies that significantly reduce the gap between design and manufacturing (Santoro & Gopalakrishnan, 2001). This would facilitate the rapid recovery of development expenditures for a particular product, as the agreements may encompass downstream operations like development and prototyping.

Stability. The transition to a knowledge-based economy is recognised as a compelling reason for industries to engage with academic institutions (Santoro & Betts, 2002). Pavitt (1988) asserts that academic research enhances the ability of corporations to address certain complicated issues. A growing body of research indicates that TIIC effectively fosters the establishment and development of technology-driven enterprises, especially SMEs, for

commercial expansion (Klofsten & Jones-Evans, 1996). The absence of in-house research and development within the industry is identified as a significant impetus for collaboration with higher education institutions. Lopez-Martinez et al. (1994) demonstrated that the absence of internal capabilities for conducting technical research was the primary incentive for business executives. According to Schartinger, Rammer, Fischer, and Fröhlich (2002), collaboration is esteemed even among organisations with R&D, since it mitigates risk and optimises scarce resources, including people and capital assets. Additionally, access to research networks that include other higher education institutions and companies, along with the possibility of intricate collaborations through consortia comprising multiple firms, higher education institutions, and other partnerships, serve as incentives for industry to engage in collaboration with higher education institutions (George et al., 2002).

Legitimacy. Siegel, Waldman, and Link (2003) noted that companies can frequently improve their image and reputation by affiliating with a distinguished institution. Affiliations with esteemed and renowned organisations, such as prominent research tertiary institutions, could augment a company's credibility among influential stakeholders (Hong & Su, 2013; Mian, 1997).

3.5 What is the process by which TIICs are established and implemented?

Numerous models on the genesis of TIICs are documented in the literature (e.g. Tuten & Urban, 2001). The Mitsuhashi (2002) model for business-to-business alliance building is deemed pertinent for the adaption of TIICs formation. Mitsuhashi delineates the process of alliance formation in five stages, commencing with the identification of alliance opportunities and concluding with the execution of the agreement. A revised iteration of Mitsuhashi's model is illustrated in Table 3 for TIIC development, grounded in the evidence derived from the systematic review. The number of stages in the construction of a certain organisational structure of TIIC is contingent upon its level of formality and complexity. The initial two phases of Mitsuhashi's methodology (Defining Alliance Opportunities and Identifying Prospective Partners) have been consolidated into Stage 1 (Partnership Identification) in Table 3. The third procedure in Mitsuhashi's approach, referred to as Making Contacts, has been retained as Stage 2, designated Make Contact. The fourth procedure in Mitsuhashi's paradigm, termed Due Diligence, is delineated into two parts in Table 3: Stage 3 (Partner Assessment and Selection) and Stage 4 (Partnership Negotiation). The final procedure in Mitsuhashi's approach, previously termed Making Deals, is now designated as Agreement Signing, Stage 5 in Table 3. The initial stage in forming a TIIC is to define the partnership's purpose, followed by identifying a partner. A variety of criteria have been proposed for partner selection. Barnes et al. (2002) recommend that regardless of the criteria for partner selection, a thorough evaluation of potential partners should be conducted, as significant advantages may be derived from this process, particularly in ensuring that the collaboration is tailored to the specific TIIC.

A characteristic highlighted in the research that aids partner evaluation is pre-existing relationships. Numerous research indicates that the results of TIICs improve when partners possess prior collaborative experiences (e.g. Dill, 1990; Geisler, 1995). Culati and Gargiulo (1999) assert that pre-existing relationships between partners are significant, as prior experiences with a potential partner may foster trust between organisations. This inter-organizational trust is gradually established through repeated interactions and mutual adaptations to the expectations, developments, and requirements of previous alliances. Schartinger, Schibany, and Gassler (2001) concur and assert that prior collaborative experience is essential, as satisfaction with previous interactions—on personal, technological, and scientific dimensions—diminishes interpersonal and institutional barriers, hence increasing the

likelihood of tertiary institution-industry collaboration (TIIC). Peterson (1995) emphasises the necessity of explicitly delineating the managerial and administrative obligations of the TIIC, including financial accountability, during the formation stage. Furthermore, Peterson proposes that a cohesive organisational framework, appropriate for the partners and the partnership's goals, should be established under the guidance of a general manager appointed by the partners. Moreover, the equitable involvement of participants in guiding the collaborative endeavour is essential (Peterson, 1995). The project plan, characterised by Buttrick (2000) as a critical success factor, must be jointly endorsed by the partners, with clearly defined milestones. Moreover, Peterson (1995) posits that success metrics must be established, interim and final deliverables delineated, and all discrepancies among partners reconciled to prevent disputes during the partnership.

Table 3. TIIC formation process

Stages	Steps
Formation process	– Establish the purpose
Stage 1: Partnership Identification	– Obtain general knowledge of the capabilities of potential partners – Consider pre-existent relationships
Stage 2: Make Contact	– Identify prospective partners –
Stage 3: Partner Assessment and Selection	– Objectively assess the strategic interests of the potential partners – Analyze actual versus professed capabilities of potential partners – Determine and organize the appropriate mix of partners – Choose the partners
Stage 4: Partnership Negotiation	– Define the partnership – Define and agree on the partnership's documented purpose or mission/vision – Determine the specific common goals/objectives for the particular effort – Define the organizational structure of the partnership – Define the management and administration of the partnership with clearly defined responsibilities – Agree on the plan – Specify the milestones – Identify the measures/indicators for success – Specify the interim and/or final deliverables
Stage 5: Agreement Signing	– Preparation and signing of collaboration agreement and/or intellectual property agreement

Upon establishing the relationship, it is imperative, contingent upon the formality and intricacy of the TIIC, to formalise it with a legal contract (Kanter, 1994). However, the significance of commitment is paramount, sustained not solely by formal agreements but also by informal dedication cultivated through camaraderie and mutual trust (Babaa, Shichijo, & Seditac, 2009). Peterson (1995) recommends that the legal document, which may serve as the intellectual property agreement for certain TIICs, must delineate all relationships and agreements among the partners, both throughout the research collaboration and after the project's conclusion, and it should receive approval from all partners. Subsequent to the establishment of the TIIC, the relationship transitions into an operational phase (Sherwood et al., 2004), characterised by a continuous process of learning and evolution (Ritter & Gemu"nden, 2003), wherein various factors either facilitate or impede the relationship (these factors are detailed below). During the operational phase, several actions occur among the organisations aimed at fulfilling the

objectives of the TIIC (Ritter & Gemu"nden, 2003). The activities and their occurrences are summarised in Table 4.

Table 4 was created by extracting pertinent themes from the studies included in the systematic review and categorising them into six sub-headings: (1) Meetings & Networking; (2) Communication; (3) Training; (4) Personnel Mobility; (5) Employment; and (6) Other Activities. The frequency and quantity of actions within a specific organisational structure of TIIC were determined to be contingent upon the formality and intricacy of the relationship.

3.6 What variables assist or impede the operation of TIIC?

Numerous factors that either promote or obstruct the functioning of TIICs were identified in nearly all reviewed studies, corroborating the assertion by various researchers that the literature on the factors influencing TIIC is indeed extensive (Bruneel et al., 2010; Cricelli & Grimaldi, 2010). The factors, if properly handled, were determined to positively influence the perceived success of knowledge and technology transfer. Conversely, when the same characteristics were overlooked or poorly managed, there was often a comparable detrimental effect on the perceived efficacy of knowledge and technology transfer. The factors are encapsulated in Table 5, categorised under seven headings: (1) Capacity and Resources; (2) Legal Issues, Institutional Policies, and Contractual Mechanisms; (3) Management and Organisational Issues; (4) Technological Issues; (5) Political Issues; (6) Social Issues; and (7) Miscellaneous Issues. Table 5 was produced by utilising the initial two categories (i.e. Capacity and Resources, and Legal Issues, Institutional Policies, and Contractual Mechanisms) from Fairweather (1991), while devising the subsequent five categories to align with the identified sub-themes.

The array of parameters substantiated Barnes et al.'s (2002) assertion that the efficacy of a collaborative project is dictated by a complex interplay of elements, alongside the aggregate effect of both adverse and beneficial influences from those elements. Moreover, among the total identified factors, those pertaining to management and organisation constituted 45%, surpassing all other categories. This aligns with the findings of Siegel, Waldman, and Link (2003), which indicated that organisational and managerial issues are pivotal factors that either facilitate or impede relationships between tertiary institutions and industry.

3.7 What are the results of TIIC?

Like any other form of inter-organizational interaction, TIIC presents distinct advantages and disadvantages for both entities involved. Numerous research (e.g. Geisler, 1995; Lee, 2000) have correlated motivations with the rewards later attained in TIIC. Nonetheless, not all advantages can be shown by the aforementioned motivations. Consequently, the particular advantages delineated in the studies are addressed individually in this section.

Table 4. Activities during TIIC

Activities	Results
Meetings & Networking	– Meetings (often in a formal way) – Conferences/Workshops/Seminars/Symposia/Forums – Expositions, TradeShows/Fairs/Exhibitions – Informal social gatherings (e.g. U-I get-togethers, breakfast meetings) – Networking activities (the process of contacting and being contacted and maintaining these relationships/links)
Communication	– Communications by voice/mail/email/conference calls (formal or informal) – Publications or co-publications of research papers, reports, newsletters, booklets, bulletins, pamphlets

Training	– Tailored educational programmes for industrial personnel – Internships in company for students – Students' involvement in industrial projects – Joint supervision of Masters degree dissertations and PhD Thesis by academic and industry personnel – Industrial fellowships for students and faculty – Industry involvement in curriculum development
Personnel Mobility Employment	– Exchange of personnel to work at one another's research facilities – Lectures by industry members at tertiary institutions and vice versa – Employment of tertiary institution researchers in the business sector – Employment of graduates particularly those related to the project

3.8 Advantages that contribute to the overall economy

1. Economic;
2. Institutional Benefits (i.e., advantages obtained by Tertiary institutions and Industry); and
3. Social Benefits (i.e., advantages pertaining to communal engagement or fostering sociability), as seen in Table 6.

Conversely, numerous disadvantages have been noted in the literature, with certain researchers contending that while the advantages of TIIC significantly surpass any risks, it is crucial for both higher education institutions and industry, especially the former, to acknowledge the potential drawbacks. This recognition is essential for implementing robust policies and administrative procedures (Harman & Sherwell, 2002) to prevent failure and ensure the success of the partnership. The disadvantages have been categorised into four relevant classifications: (1) Deviation from Mission or Objective; (2) Quality Issues; (3) Conflicts; and (4) Risks. Table 6 consolidates these limitations for both higher education institutions and industry. Notably, research on TIIC predominantly focusses on tertiary institutions rather than industry when examining its possible disadvantages. This can be elucidated by examining the motivations of tertiary institutions about TIIC. Table 2 reveals that access to research funding is the predominant reason for tertiary institution-industry collaboration among tertiary institutions in the literature. Tertiary institutions, motivated primarily by economic factors and informed by resource dependence theory (Pfeffer & Salancik, 1978), are likely to occupy a precarious position due to their diminished power and control over agreements, a common characteristic in cross-sector collaborations involving industry as a principal stakeholder (Al-Tabbaa, Leach, & March, 2014). This precarious situation is likely to engender numerous other problems, such as industry pressure for expedited outcomes or the potential restriction of knowledge distribution generated by the TIIC in accordance with industry demands.

Table 5. Factors facilitate or impede TIICs

Main categories	The factors
Capacity and Resources	– Adequate resources (funding, human and facilities) – Incentive structures for tertiary institution researchers – Recruitment and training of technology transfer staff – Capacity constraints of SMEs
Legal issues, and Contractual Mechanisms	– Inflexible tertiary institution policies including intellectual property rights (IPR), patents, and licenses and contractual mechanisms – Treatment of confidential and proprietary information - Moral responsibility versus legal restrictions (research on humans) –

Management and Organization Issues	– Leadership/Top management commitment and support – Collaboration champion – Teamwork and flexibility to adapt – Communication – Mutual trust and commitment (and personal relationships) – Corporate stability – Project management – Organization culture (cultural differences between the world of academia and of industry) – Organization structure (tertiary institution administrative structure and firm structure) – Firm size (size of organization) – Absorptive capacity – Skill and role of both tertiary institution and industry boundary spanners – Human capital mobility/personnel exchange
Issues Relating to the Technology	– Nature of the technology/knowledge to be transferred (tacit or explicit; generic or specialized; academic rigor or industrial relevance)
Political Issues	– Policy/legislation/regulation to guide/support/encourage UIC (support such as tax credits, information networks and direct advisory assistance to industry)
Social Issues	Enhancement in reputation/prestige
Other Issues	– Low level of awareness of tertiary institution research capabilities – Use of intermediary (third party) – Risk of research – Cross-sector differences/similarities – Geographic proximity

Table 6. TIIC outcomes

Benefits	Tertiary institutions	Industry
Economic-related	— Source of revenue (both public and private) – Patents/IPRs/licensing income – Additional income or financial benefit to researchers – Create business opportunities – Contribution to local/regional economic development	– New products and/or processes – Improved products and/or processes – Patents, prototypes, generate IPRs, etc – More cost-effective than similar research in-house – Improved competitiveness – Access public grants – Promote economic growth/enhancement of wealth creation
Institutional-related	- Exposure of students and faculty to practical problems/new ideas and/or to state-of-the-art technology, with positive effects on the curriculum – Provide a “test bed” for feedback on research ideas,	– Improved innovative ability and capacity/ Keep up to date with major technological developments – Advance new technologies – Accelerates commercialization of technologies/Increases speed of innovation to

	- results/interpretations for the refinement of academic ideas/theories – Stimulate technological advancement and/or research activities in certain key areas – Acquisition of or access to up-to-date equipment – Training and employment opportunities for students – Build credibility and trust for the academic researcher among practitioners – Stimulate the development of spin-offs (or spin-off companies) – Provide opportunity for companies to influence and encourage the development of particular lines of tertiary institution research – Joint publications with industry – Publication of papers by academics	- market – No inter-firm conflicts of interest – Provide much needed legitimacy for industry products (e.g. software programme) – Access to new knowledge and leading edge technologies and/or a wide variety of multidisciplinary research expertise and research infrastructure – Influence tertiary institution research directions and new programs for industry good – Access to specialized consultancy/Identify relevant problems/Solve specific technical problems – Product testing with independent credibility in testing – Training/continued professional development – Opportunity to access a wider international network of expertise – Act as a catalyst that leads to other collaborative ventures – Joint publications – Hiring of talent graduates
Social-related	Service to the community – Enhancement of tertiary institution's reputation	– Enhance reputation by becoming more social responsible business
Drawbacks Deviation from Mission or Objective (Core Ethic)	– Threats to research autonomy or integrity for commercial advantage that may have a negative impact on culture of open science and affect tertiary institution mission – Confidentiality agreements may block the dissemination of knowledge – Could result in the abandonment of long-term basic research in favor of results-oriented, short-term, applied research and technology transfer – Concern that the end result of collaboration could be short-term contracts in which industry would require 'quick and dirty' solutions to problems, with tertiary institution departments acting as extensions to the research activities of firms	– Slow academic bureaucracies may stifle technology commercialization, depress the firm's performance and delay the fulfillment of the firm's objectives – Diversion away from the 'bottom-line' issues of industry like return on capital investment – Collaboration may be costly due to increase in administrative overheads, as industry may have to

		develop specific managerial and administrative competencies, which may be a time-consuming process
Quality Issues	Potential diversion of energy and commitment of individual staff who are involved in interaction with industry, away from core educational activities – Could affect types of research questions addressed and reduce the quantity and quality of basic research	– Low intellectual level of some contract work – Results in theoretical and impracticable solutions since tertiary institution staff are too theoretical and not very practical whereas industry's focus is much more problem centered on critical situations requiring immediate attention
Conflicts	Conflicts between researchers and company over the release of adverse results/damage in professional relationships among the researchers – Biased reporting by researchers sponsored by companies in favor of positive experimental results relating to company products	– Disharmony and discord during R&D development – Intellectual property disputes and patenting disagreement
Risks	— Dilemma of either publishing results for short-term revenue and academic recognition or withholding until they are patented, with the risk of the technology becoming obsolete – Risks that academic—industry relationships pose to human subjects of research and to the integrity of academic investigation	– Diminished control or leakage of proprietary information – High failure rate of collaborations – Financial risk to industry – Risk of incomplete transfer or non-performance of technology – Market risk where there is uncertainty of the success of the product launched in the market

4. DISCUSSION

The partnership between higher education institutions and industry is primarily seen as a method to enhance economic innovation by promoting the transfer and application of technology-related knowledge and expertise across sectors (Inzelt, 2004; Perkmann, Neely, et al., 2011). This collaboration possesses two different traits. TIIC represents a collaborative framework between higher education institutions and commercial organisations for the

interchange of both tangible resources (such as funding, materials, and equipment) and intangible resources (including technology and data) (Perkmann et al., 2013). Secondly, akin to cross-sector collaboration (e.g., Kindred & Petrescu, 2014; Kivleniece & Quelin, 2012), partners generally possess both distinct (e.g., academic publishing for higher education institutions and technical problem-solving for industry) and shared objectives (e.g., generating impact by delivering solutions to societal issues) that motivate their collaborative efforts. This illustrates the strategic impact of collaboration, as TIIC is perceived as a logical process. Strategic effect transpires when organisations justify their inter-organizational ties as a means to obtain the resources they lack (Airto, 2001; Koka & Prescott, 2002). In other terms, TIIC is seen as a logical process when it is predominantly pursued for the aggregation and exchange of various resources.

TIIC, as a distinct type of inter-organizational connection, can be perceived as a process aimed at knowledge production, resulting in the generation of new knowledge that neither party previously held (Hardy, Phillips, & Lawrence, 2003; Mowery, Oxley, & Silverman, 1996). In this context, knowledge is viewed as a tacit, context-dependent entity, rather than a codifiable and transferable resource between organisations, generated through continuous social interactions among the actors of the partners throughout the duration of the collaboration (Powell, Koput, & Smith-Doerr, 1996). This indicates that the efficacy of collaboration, regarding knowledge generation, can be assessed by the diversity and strength of an organization's external connections (Huggins, Johnston, & Thompson, 2012; Nonaka, 1994; Simonin, 1997). Consequently, Powell et al. (1996) propose that a distinction be made between information transmission and knowledge generation when examining collaboration outcomes. The former views the inter-organizational interaction as a rational process that delineates the objectives of the relationship, along with the extent and scope of each organization's participation. In the latter scenario, collaboration is characterised as an illogical, informal, and unstructured process wherein the relationship between two organisations develops organically through unanticipated and ongoing encounters among participants from both entities. This discussion concludes that TIIC may be perceived as either a rational process, emphasising planned resource and knowledge transfer, or an irrational process, where knowledge production occurs through informal social interactions between organisations. Nevertheless, our study revealed that the perception of TIIC as a rational process is predominantly represented in the TIIC literature. This perspective may be elucidated by the process through which the partnership is executed, strategised, and implemented. Generally, every TIIC undergoes an extensive evaluation process by both partners prior to the formulation and signing of an agreement (Bruneel et al., 2010). Two primary issues necessitate comprehensive assessment and investigation.

Due to economic pressures, stakeholders of tertiary institutions and companies hold elevated expectations for their organisations to exhibit accountability and effectiveness in resource utilisation when forming inter-organizational connections (Nahapiet & Ghoshal, 1998). For instance, governmental and other funding entities anticipate that tertiary institutions will employ TIIC to tackle societal social or economic issues (e.g., enhancing the employability of graduates), while corporate shareholders expect their companies to pursue TIIC to ascertain the commercialisation of new technologies (Adler & Kwon, 2002). Secondly, collaboration across sector borders poses the potential of mission creep for tertiary institutions (cf. Careya, Lawsonb, & Krausec, 2011). This occurs when the primary goals and functions of tertiary institutions are affected by the commercial objectives of their business partners. Furthermore, as noted in the disadvantages section, tertiary institutions may experience reputational harm if any of its commercial partners engage in unethical or socially unacceptable conduct. This

danger is particularly pertinent as, in recent years, business has increasingly been perceived as a significant contributor to social, environmental, and economic issues. Corporations are commonly viewed as thriving at the detriment of the larger community (Porter & Kramer, 2011, p. 64). Based on these two issues, the prevailing view of TIIC as a rational process is justifiable, as both partners aim to identify specific and measurable objectives for their interaction, plan requisite procedures or activities, and clarify the potential impact on organisations and society. Moreover, perceiving TIIC as a rational process would enable higher education institutions to judiciously choose their business partners and delineate the parameters of their engagement regarding resources and responsibilities, thereby safeguarding these institutions from the potential loss of legitimacy should their partners' reputations decline due to social or environmental transgressions. A methodical procedure is essential to structure this relationship and prevent tertiary institutions from straying from their primary objective: education and knowledge advancement.

Nonetheless, we do not want to reach a normative conclusion in this context. We do not contend that the logical perspective is superior than the irrational one in the examination of TIIC. We want to offer an explanatory account of the predominance of the rational perspective in the existing literature, as evidenced by our analytical findings. Although infrequent in literature, the irrational perspective remains a significant and complementary theoretical framework for analysing the nature of TIIC. Understanding collaboration as a political and social interaction process is crucial for comprehending how knowledge is generated when partners from diverse sectors, such as academic institutions and industry, work together. Furthermore, the irrational perspective is pertinent when examining the development of informal 'personalised' collaboration between organisations, including higher education institutions and industry (De Carolis & Saporito, 2006), where "certain critical R&D practices appear to pursue their own paths and 'rationalities' independent of deliberate managerial oversight and direction" (De Carolis & Saporito, 2006, p. 190). Consequently, examining the influence of both informal and formal relationships and social interactions is crucial for comprehending the innovation process in TIIC (Dess & Shaw, 2001), as this process is fundamentally based on the socially embedded nature of knowledge creation (Sirmon, Hitt, & Ireland, 2007).

4.1 The foundational philosophy of TIIC: advancing an integrated perspective

As previously said, TIIC in the literature has been perceived as both a rational and an irrational process. This indicates that scholars in this field highlight the significance of interdependency (the rational perspective of TIIC) and interaction (the irrational perspective of TIIC) theories in the formation, evolution, and sustenance of these connections. Interdependency theories emphasise the influence of the external environment on the establishment of TIIC, whereas interaction theories examine the internal development and sustenance of these relationships (Geisler, 1995).

The literature presents various perspectives on interdependency theories, including sociological viewpoints, behaviorally-oriented paradigms, and those derived from economics. Six prevalent viewpoints have been identified (Barringer & Harrison, 2000), namely: Transaction Cost Economics, Resource Dependency, Strategic Choice, Stakeholder Theory, Organisational Learning, and Institutional Theory. Transaction Cost Economics (TCE) posits that transactions, or economic exchanges, serve as the fundamental unit of analysis for an organization's economic interactions, which aim to minimise production costs and enhance efficiency (Tadelis & Williamson, 2012). Consequently, it may elucidate the rationale behind the propensity of educational institutions and corporations to establish partnerships aimed at reducing their technological development expenditures. Nonetheless, TEC faces criticism for

its narrow emphasis on efficiency maximisation and cost minimisation, neglecting other significant factors such as relational learning (Dekker, 2004). Likewise, the Resource Dependency (RD) theory may elucidate the motivations for Tertiary institution-Industry Collaboration (TIIC), as both academic institutions and the industry regard themselves as reliant on resources. Although RD theory is highly enticing, it possesses many limitations. It primarily neglects to elucidate why organisations may opt for alternative strategies beyond alliances to address perceived resource deficiencies, such as raising new capital to acquire resources through market transactions (Child, Faulkner, & Tallman, 2005), which is frequently preferred over alliance formation. Furthermore, not every organisation within an inter-organizational field serves as a viable resource for the other party (Pennings, 1981; Powell et al., 1996), reflecting the irrational process perspective of TIIC. The Strategic Choice (SC) theory is a valuable theoretical framework that elucidates organisations' strategic decisions regarding competitiveness. Decisions are deemed reasonable if they cultivate a competitive advantage for a corporation or enable it to acquire greater influence in a certain market (Santos & Eisenhardt, 2005). This viewpoint may also be pertinent, as higher education institutions and corporations may collaborate for strategic purposes (e.g., advantages from economies of scale in collaborative research or expedited access to emerging technology). Nonetheless, a significant flaw of this theory is the lack of consensus on categorising the various extant TIIC techniques into coherent categories for analysis (Barringer & Harrison, 2000). Furthermore, techniques exhibit varying degrees of success across different contextual situations (Kent, 1991).

Stakeholder Theory (ST) posits that an organization's stakeholder groups—individuals or entities that can influence or are influenced by the organization's aims (Freeman, 1984)—are crucial for sustaining its social legitimacy (Dacin, Oliver, & Roy, 2007). Organisational legitimacy is attained when its operations align with the societal norms and regulations of its operational context (Zukin & Dimaggio, 1990). Consequently, by contemplating the TIIC environment, higher education institutions and corporations may pursue partnerships to enhance their comprehension of and regard for the objectives of all pertinent stakeholders in their principal operational and strategic choices (Adler & Kwon, 2002). Despite its robustness, stakeholder theory is characterised by ambiguity regarding the prioritisation of stakeholder interests (Langtry, 1994), and it is deficient in context and causal laws to elucidate the process (Jensen, 2002). Learning Theory (LT) underscores the significance of information in establishing and sustaining competitive advantages (Larsson, Bengtsson, Henriksson, & Sparks, 1998). However, due to the often tacit nature of knowledge, which complicates its valuation and acquisition in the marketplace, an organisation seeking to acquire a specific skill is more likely to succeed by establishing a partnership with an organisation that excels in that domain (Barringer & Harrison, 2000). From this viewpoint, it can be asserted that TIIC occurs to leverage learning chances, as TIIC is very proficient in facilitating knowledge exchange among organisations (Hoffmann & Schlosser, 2001). While the LT seems conceptually appropriate for elucidating TIIC, a limitation of the theory is its focus on competency and skill development and transfer, neglecting the associated costs and the risk of losing proprietary information beyond the intended scope of collaboration (Hamel, Doz, & Prahalad, 1989). Finally, Institutional Theory (IT) posits that organisations face institutional forces that compel them to adopt particular practices to align more closely with the norms of their external contexts (DiMaggio & Powell, 1983). Motivated by these forces, tertiary institutions and business may pursue partnership to attain legitimacy and adhere to established societal standards, as a consequence of institutional pressure. A firm may pursue TIIC to project an image of "social responsibility" by investing in societal issues through partnership, while tertiary institutions may aim for TIIC to enhance practical relevance and so be viewed as effective and accountable.

However, it emphasises institutionalisation as a conclusion rather than a process, so disregarding the influence of power (Zucker, 1987) and group interests (Perrow, 1986). Furthermore, it is challenging within the realm of IT to elucidate the rationale behind the existence of certain interaction forms, particularly when they deviate from the status quo (Barringer & Harrison, 2000).

Interaction theories (ITs), including the social network approach (e.g., Borgatti & Molina, 2003; Brass, Galaskiewicz, Greve, & Tsai, 2004), are crucial in comprehending the formation, assessment, and sustainability of TIIC (Geisler, 1995). The ITs view tertiary institutions and industry as autonomous entities, suggesting that a partnership could commence if either entity takes the initiative. Furthermore, the establishment of organisational connections may be enhanced by pre-existing relationships (Turnbull, Ford, & Cunningham, 1996). Consequently, the ITs elucidate the dynamics of TIIC and the evolution of relationships through the increasing importance of commitment, trust, and communication (Levinthal & Fichman, 1988; Ritter & Gemu"nden, 2003). Nonetheless, these theories are constrained as they primarily emphasise the continuous social interactions among organisational actors, while neglecting the significance of managing TIIC as a rational strategy that necessitates a premeditated and systematic perspective on the collaboration process and its anticipated results, as previously elucidated. The ITs assert that inter-organizational cooperation emerges within particular relationships and develops via continuous interaction (Heide & Miner, 1992). In other words, ITs focus on the relationship process dynamically, in contrast to the static and preset nature of interdependency theories (Geisler, 1995).

4.2 A systematic examination of partnership between tertiary institutions and industry

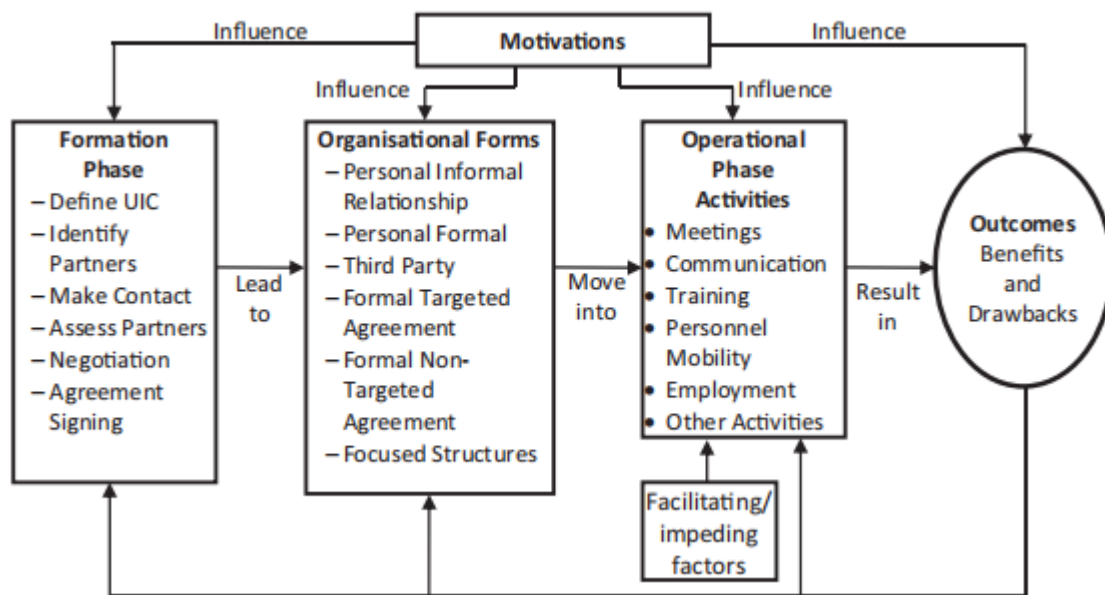


Figure 1. Conceptual framework for TIIC: a comprehensive perspective.

Although interdependency and interaction theories have yielded significant insights into particular elements of TIIC, they are insufficient for constructing a comprehensive understanding of this phenomenon. This suggests a lack of a middle-range theory, which is situated between the large theories of interdependency and interaction, that may explain both the observed phenomena and the systematic explanations of specifics in TIIC. Consequently, the results of the review are effectively incorporated into the conceptual framework illustrated

in Figure One. Depending on the intricacy of the relationship, a certain type of TIIC may bypass certain stages of the formation phase and may not undergo all operational phase activities or achieve all objectives.

The interaction between the two organisations arises from their shared influences and diverse motivations. The construction of relationships results in a specific organisational structure based on the objectives or motivations of the connection in question. Subsequent to the formation, the connection transitions into the operational phase, marked by diverse activities and influenced by several elements that either promote or hinder the partnership. The connection has yielded several advantages and certain disadvantages for both organisations as a result. While the motivations of both organisations are crucial to the relationship, they must also recognise the factors that facilitate and hinder this relationship, as well as its potential drawbacks. This awareness enables them to implement well-developed policies and administrative procedures, as noted by Harman and Sherwell (2002), to ensure the successful achievement of both organisations' objectives. Feedback loops from the "Outcomes" to the other primary stages suggest that the TIIC may be altered as a consequence of the outcomes. Conclusions and avenues for future research

This report delineates the findings of a systematic review on TIIC covering the period from 1990 to 2014. Out of more than 1500 studies deemed relevant to the issue, 109 were selected. The investigations were subsequently analysed in relation to five inductively identified features using techniques from qualitative data analysis. The primary aspects, represented by the five questions, were categorised into several sub-themes, which were subsequently analysed for both tertiary institutions and industry. A comprehensive procedural structure was established to integrate the diverse components of the review.

The review and framework have significantly contributed by offering a coherent integrated analysis of the literature's current condition and highlighting areas necessitating additional exploration. The review indicated that the assessment of technology translation outcomes, encompassing the advantages and success of the partnership, is typically reliant on the evaluations of industry or higher education stakeholders, who may have established the results by contrasting prior needs and expectations with subsequent actual or perceived satisfaction. Nonetheless, a challenge related to this form of evaluation is that stakeholders from the business and higher education institutions may differ in their definitions of the success of the interaction and its results (Barnes et al., 2002). Consequently, it is essential to explore additional methods to more scientifically assess the efficacy of TIIC, beyond the already utilised subjective metric. To what degree can the quantity of new patents, products, and publications accurately represent the true value of the TIIC and substantiate its cost and risk? Similarly, it is essential to investigate whether higher education institutions would benefit more from persisting in the creation of spin-out firms or if they should confine their goals to roles that do not replicate industrial functions. There is insufficient data concerning the optimal metrics for assessing these spin-outs, including financial returns and survival rates (Lockett & Wright, 2005). The influence of intellectual participation in the TIIC process is largely neglected. None of the examined studies have investigated the impact of this engagement on the teaching and learning experiences of students associated with higher institutions that collaborated with the sector. This research may offer corroborative evidence for the intangible potential worth of the TIIC (Perkmann et al., 2013).

Third, the evaluation clearly indicated the necessity to assess the degree to which the TIIC may transition from a complementary resource strategy to one that leverages the competitive

advantages of the participating companies. Although numerous research (e.g. Das & Teng, 2000) exist about within-sector collaboration (i.e. business to company), it is uncertain whether this approach is applicable to TIIC. For instance, can the intellectual exchange and novel perspectives of academic collaborators, stemming from their continual engagement with cutting-edge information, substitute for or at least enhance a company's R&D capabilities? A valid study conclusion in this area can significantly influence industry investment decisions in TIIC. Fourth, further investigation is required to analyse the government's participation in TIIC. In developed countries, research indicates that the government plays a crucial role in fostering the establishment and advancement of such partnership (Perkmann, Neely, et al., 2011). Nonetheless, it remains uncertain whether governance in rising and developing nations, whose tertiary institutions are regarded as wholly or partially public entities, would adhere to the same trend. The institutional relationship among tertiary institutions, industry, and government, known as the Triple-Helix model, comprises three primary configurations (Ranga & Etzkowitz, 2013):

- (1) government directs the tertiary institution-industry collaboration (TIIC) by establishing objectives and constraints for their interaction,
- (2) industry serves as the principal force in the TIIC, with tertiary institutions and government playing limited roles—tertiary institutions provide academic talent while government regulates social and economic mechanisms,
- (3) all three entities collaborate as partners to facilitate the transfer of knowledge to society, with the tertiary institution potentially assuming a leadership role in this arrangement.

Although Ranga and Etzkowitz (2013) propose that the latter configuration provides the most significant insights for innovation, its validity across all economies remains uncertain. Consequently, a crucial aim for forthcoming study is to investigate whether government participation should occur at all stages of collaboration or be restricted to particular phases (e.g., funding and policy formulation). Similarly, with TIIC in underdeveloped nations, additional enquiries may encompass how corporations might avert knowledge leaking when partnering with public tertiary schools that lack adequate regulatory frameworks to safeguard their intellectual property and proprietary information. Fifth, it is essential to perform comparison studies on TIIC across various countries. It is uncertain if this type of connection can thrive under these settings (Hong, Heikkinen, & Blomqvist, 2010). Moreover, research in this domain can examine the degree to which inter-country TIIC can enhance the national innovation capability of the host country (Jin, Wu, & Chen, 2009). We contend that research in this domain should not focus on validating existing theories or concepts related to TIIC; instead, it is essential to cultivate both theoretical and empirical comprehension of the factors that facilitate or hinder the emergence of global TIICs, such as cultural implications, policy inconsistencies, and misalignment of national objectives. Ultimately, our analysis indicates that the predominant category of the examined papers consists of cross-sectional research. Consequently, a longitudinal study approach is necessary to yield further insights into causal dynamics and to evaluate the 'worth' of the comprehensive results of these interactions across both short-term and long-term periods.

5. CONCLUSION AND PATHWAYS TO FUTURE RESEARCH

This paper presents the results of a systematic review on TIIC for the period 1990—2014. 109 studies were selected out of over 1500 studies considered as being pertinent to the topic. These studies were then analyzed against five inductively- identified aspects by means of techniques from the field of qualitative data analysis. In the process, the main aspects (embodied by the five questions) were subdivided into various sub-themes, which were further analyzed for the two parties, tertiary institutions and industry. Finally, an overarching process framework was

developed to link together the various elements of the review.

The review and framework have not only provided a substantial contribution by creating a clear integrated analysis of the state of the literature, but also have indicated areas that require further investigation. First, it was observed through the review that the evaluation of the outcome of technology translation, including the benefits and the success of the alliance, is normally based on the judgment of industry or tertiary institutions actors who might have determined the outcomes by comparison of a prior needs and expectations and a posteriori, actual or perceived satisfaction. However, one of the problems associated with this type of evaluation is that the actors from the industry and tertiary institutions may vary in definition of the success of the inter- action and its outcomes (Barnes et al., 2002). Therefore, there is a need to investigate other alternatives to more objectively measure the effectiveness of UIC, in addition to the subjective measure currently employed. For example, to what extent the number of new patents, products, publication can reflect the real value of the UIC and justify its cost and risk. In the same vein, there is a need to explore whether tertiary institutions would be better off by continuing to be involved in the generation of spin-out companies or whether they should limit their objectives to functions that do not duplicate the function of industry. Specifically, there is no sufficient evidence regarding the best dimensions to evaluate these spin-out, such as financial gains and rate of survival (Lockett & Wright, 2005). Second, the impact of academic engagement in the process of UIC is almost overlooked. For example, none of the reviewed studies have addressed the consequences of this engagement on, for example, teaching and learning experience of students affiliated to tertiary institutions that engaged with the industry. This line of research can provide supporting evidence to the intangible potential value of the UIC (Perkmann et al., 2013). Third, it was evident in the review that there is a need to examine the extent of which the UIC can move from resources complementary approach to be utilized in leveraging the competitive advantages of the engaged companies. Despite several studies (e.g. Das & Teng, 2000) that can be found in the area of within- sector collaboration (i.e. business to business), it was unclear whether this would work in the case of UIC. For example, do the intellectual exchange and the fresh perspective of academic collaborators (resulting from their consistent interaction with the state-of-art knowledge) can replace or at least contribute to the R&D capabilities of a company. Valid research outcome in this direction can be critical in affecting the decision making regarding the investment in UIC by the industry. Fourth, more research is needed to examine the role of government in UIC. In the developed economies, research shows that government is a key player in facilitating the establishment and development of such collaboration (Perkmann, Neely, et al., 2011). However, we do not know if government in the emerging and developing countries, where tertiary institutions are considered as pure or semi-public institutions, would follow the same pattern. In principle, the institutional relationship between the tertiary institution, industry and government (or the Triple-Helix model) has three main configurations (Ranga & Etzkowitz, 2013):

- (1) government leads the UIC by defining objectives and putting limitations for the interaction between tertiary institution and industry,
- (2) industry becomes the driving force for the UIC, where both tertiary institution and government have limited roles (tertiary institution acts as provider of academic talents, where government role is to regulate the social and economic mechanisms),
- (3) the three actors act as partners aiming for the transition of knowledge to society, however the tertiary institution can take the lead in this configuration.

Despite Ranga and Etzkowitz (2013) suggest that the latter configuration offers the most important insights for innovation, we are not sure if this suggestion is valid in all economies.

Therefore, an important objective for future research is to examine whether it is better that government intervenes at all collaboration stages, or limit this intervention at specific stages (e.g. funding and policy-making). In the same vein (i.e. UIC in developing economies), other questions might include how companies can prevent knowledge-leakage when collaborating with public tertiary institutions that lacks proper legal systems to protect their intellectual properties and know-how secrets. Fifth, there is a need to conduct comparative studies across different countries in relation to UIC. We do not know whether this kind of interaction can succeed in such conditions (Hong, Heikkinen, & Blomqvist, 2010). Furthermore, research in this area can investigate the extent of which inter-country UIC can contribute to the national innovation capacity of the hosting country (Jin, Wu, & Chen, 2009). Yet, it is our belief that studies in this area should not be pursued as testing existing theories/concepts about UIC, but rather there is a need to develop theoretical and empirical understanding regarding the circumstances that promote and/or restrict (e.g. cultural implication, policies inconsistencies, mismatching of national objectives) the emergence of global UICs. Finally, our study reveals that the majority of the reviewed papers are actually cross-sectional studies. Therefore, there is a need for longitudinal line of research to provide additional insights into cause and effect dynamics and also help in assessing the ‘value’ of the full range of outcomes of these relationships in both short term and long-term scales.

Appendix A

Journal title	Total no. of articles	Articles included in the analysis
<i>Technovation</i>	11	Acworth (2008), Arvanitis, Kubli, and Woerter (2008), Babaa et al. (2009), Bekkers and Bodas Freitas (2008), Boardman and Corley (2008), Bodas Freitas, Marques, and Silva (2013), Bruneel et al. (2010), D'este and Patel (2007), Eom and Lee (2010), Etzkowitz (1998), Etzkowitz and Leydesdorff (2000), Feller et al. (2002), Fontana, Geuna, and Matt (2006), Giuliani and Arza (2009), Hayashi (2003), Hong and Su (2013), Inzelt (2004), Kaufmann and Tödtling (2001), Lee (1996), Lehrer et al. (2009), Lockett and Wright (2005), Mansfield and Lee (1996), Meyer-Krahmer and Schmoch (1998), Motohashi (2005), Mueller (2006), Pavitt (1988), Santoro and Chakrabarti (2002), Scharfetter et al. (2002), Segarra-Blasco and Arauzo-Carod (2008), Siegel, Waldman, and Link (2003), Welsh, Glenna, Lacy, and Biscotti (2008), Woolgar (2007) and Wright et al. (2008)
<i>R&D Management</i>	9	Bonarccorsi and Piccaluga (1994), Chiesa and Manzini (1998), Dill (1990), Enkel and Gassmann (2010), Jacob et al. (2000), Lee (2011), López-Martínez et al. (1994), Perkmann, Neely, et al. (2011), Plewa, Korff, Baaken, and Macpherson (2013)
<i>Journal of Technology Transfer</i>	10	Abramo, D'angelo, Di Costa, and Solazzi (2011), Caloghirou et al. (2001), Hall et al. (2001), Lee (2000), Muscio and Pozzali (2013), Okamuro and Nishimura (2013), Ponomarev (2013), Santoro and Gopalakrishnan (2001), Scharfetter et al. (2001), Thune and Gulbrandsen (2014)
<i>International Journal of Technology Management</i>	4	Autio and Laamanen (1995), Howells and Nedeva (2003), Shenhar (1993), Wong (1999)
<i>IEEE Transactions on Engineering Management</i>	4	Gopalakrishnan and Santoro (2004), Santoro and Saporito (2006), Santoro and Chakrabarti (2001), Santoro and Saporito (2003)
<i>Journal of Business Venturing</i>	4	George (2002), Harmon et al. (1997), Mian (1997), Soh and Subramanian (2014)
<i>International Journal of Management Reviews</i>	3	Agrawal (2001), Dess and Shaw (2001), Santoro and Chakrabarti (1999)
<i>Technology Analysis & Strategic Management</i>	3	Bell (1993), Blackman and Seagal (1991), Geisler (1995)
<i>Academy of Management Review, European Management J., J. of Management, Long Range Planning, American J. of Sociology, Organizational Dynamics, J. for Higher Education Management, Management Science, Organization Studies, J. of Higher Education Policy and Management, Industry and Higher Education, J. of Product and Brand Management, American Business Law J., Computers Industrial Engineering, J. of Engineering and Technology Management, European J. of Innovation Management, Research Technology Management, Oxford Review of Economic Policy, J. of Product innovation</i>	28 (28 articles from 28 different journals.)	Ring and Van De Ven (1994), Barnes et al. (2002), Barringer and Harrison (2000), Bower (1993), Culati and Gargiulo (1999), Cyert and Goodman (1997), Powers (2003), Owen- Smith, Riccaboni, Pammolli, and Powell (2002), De Carolis and Saporito (2006), Harman and Sherwell (2002), Mora- Valentin (2000), Logar et al. (2001), Newberg and Dunn (2002), Peterson (1995), Santoro and Gopalakrishnan (2000), Philbin (2008), Santoro and Betts (2002), Poyago- Theotoky et al. (2002), Duggan (1997), Siegel, Waldman, Atwater, and Link (2003), Lee (1998), Turk-Bicakci and Brint (2005), Shichijo, Baba, and Yarime (2010), Lebeau, Laframboise, Larivière, and Gingras (2008), Etzkowitz (2002), Guan and Zhao (2013), Muscio (2013), D'este, Guy, and Iammarino (2013)

management, The J. of High Technology Management Research, Policy Studies Journal, Higher education, I. J. of Innovation Management, Research evaluation, Science and Public Policy, Technological Forecasting and Social Change, Papers in Regional Science

Total number of articles included in the review 109

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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CHALLENGES AND OPPORTUNITIES FOR DEPLOYING SOLAR ENERGY IN DEVELOPING COUNTRIES

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Abstract

This article examines the evolving landscape of solar energy adoption in developing nations, specifically within the context of smart cities. Developing nations must address the energy deficit, mitigate emissions, stimulate economic growth, and improve energy security. Solar energy presents viable solutions to these difficulties. Notwithstanding the potential of solar energy, challenges persist. Financial limitations, obsolete infrastructure, grid instability, deficiencies in technical skills, and regulatory obstacles impede extensive adoption. Nevertheless, advancements in solar panels, energy storage, smart grids, and data analytics offer solutions to these difficulties. Collaborative activities, uniform policies, and public-private partnerships provide assistance for sustainable development. Intelligent urban areas are pivotal in this transformation. Sustainable urban design, intelligent infrastructure, and digitalisation enhance the efficient utilisation of solar energy. Case studies from India, Rwanda, and Brazil illustrate the effective incorporation of solar energy into smart city initiatives. Reconciling problems with opportunities is essential for success. By overcoming challenges and capitalising on opportunities, developing nations can spearhead the transition to a sustainable energy future.

1.0 Introduction

As the 21st century has begun, a new era of unparalleled global challenges has begun, with climate change being at the forefront of this new landscape. It has never been more important to have access to sustainable and renewable energy sources than it is right now, as the globe is struggling to cope with the terrible effects of rising temperatures, extreme weather events, and an impending environmental crisis. In light of the current predicament, solar energy has arisen as a ray of hope due to its capacity to supply power that is both pollution-free and abundant.

The implications of climate change are not immune to developing countries, and they frequently experience the most severe consequences as a result of these impacts. In addition, these countries are also experiencing rapid urbanisation, a process that brings forth a variety of challenges as well as benefits. The confluence of these two realities has resulted in the emergence of a significant matter of concern, which is the incorporation of solar energy into the framework of smart cities across developing countries.

2.0 Deploying Renewable Energy in Developing Countries

2.1 The General Situation

When it comes to energy, developing countries are characterised by a number of issues that are interconnected with this issue. The problem of how to get access to energy comes first and foremost. There is still a sizeable section of their populations that does not have access to dependable power, which impedes the growth of their economies, threatens their quality of life, and undermines their educational chances. It is therefore of the utmost importance for these countries to discover methods that are both sustainable and capable of bridging the energy gap, and this is where solar power comes into play.

Furthermore, the development of solar energy is strongly aligned with the objectives of reducing the effects of climate change for the better. A transition to low-carbon energy sources is something that developing nations have a vested interest in doing because they are frequently disproportionately affected by climate-related disasters. A considerable reduction in emissions of greenhouse gases and a fight against global warming can be accomplished through the use of solar energy.

The solar energy industry has the potential to be a driver of job development and a reduction in the cost of electricity, from an economic point of view. It is possible that the continued decrease in the cost of solar technology will have the effect of bolstering local economies by encouraging a culture of innovation and entrepreneurship. Furthermore, the decreased costs of energy for businesses and people can free up resources that can be used to meet other essential requirements, which, in turn, can stimulate economic growth.

When it comes to many emerging countries, energy security is another serious worry. Frequently, these countries are highly dependent on the importation of fossil fuels, which are susceptible to swings in price as well as disruptions in supply. They are able to lessen their reliance on energy sources that are imported and improve their energy security if they develop their solar potential.

2.2 Challenges on the Road to Solar Energy Adoption

However, transitioning to solar energy is not without its challenges. Financing remains a major obstacle, with developing nations frequently constrained by limited financial resources for infrastructure development. Building the necessary solar infrastructure, including solar farms, distribution networks, and energy storage solutions, requires substantial upfront investments. Infrastructure and grid integration issues pose additional hurdles. Many developing countries have outdated energy infrastructure, which must be upgraded and modernized to accommodate the fluctuations in energy supply that are inherent to solar energy. Ensuring grid stability while integrating renewable sources is a complex and costly endeavour.

Moreover, there is often a lack of technical expertise in these regions, which can hinder the effective deployment and maintenance of solar energy systems. A skilled workforce is crucial for ensuring the long-term success of solar projects. On the policy front, inconsistent regulations, bureaucratic barriers, and a lack of clear incentives can further deter investment in solar energy. These regulatory hurdles can stifle growth and innovation in the sector.

In light of these challenges, the promotion of solar energy in developing countries is not a straightforward task. However, technological advancements, policy initiatives, and the concept of smart cities offer a glimmer of hope, providing opportunities to overcome these obstacles and usher in a new era of sustainable and resilient urban development. This perspective article delves deeper into these critical dimensions, aiming to provide a comprehensive understanding of the challenges and opportunities associated with solar energy adoption in the context of smart cities within developing nations.

2.3 Solar Energy in Developing Countries

Solar energy has become an indispensable player in the global effort to address energy challenges and foster sustainable development, particularly in developing countries. Understanding the multifaceted dimensions of solar energy adoption in these regions is essential, as it holds the key to a brighter, cleaner future.

2.4 Energy Access: Alleviating Energy Poverty

Energy poverty is a pressing issue in developing countries, affecting billions of people. Far too often, individuals and entire communities lack access to reliable and affordable electricity. In rural and remote areas, the absence of electricity hampers not only daily life but also the development of crucial sectors such as healthcare, education, and economic activities. The need for increased energy access is one of the most compelling reasons to embrace solar energy. Off-grid and decentralized solar solutions, including solar home systems and mini-grids, are empowering communities that were once left in the dark. These solutions provide an affordable and sustainable source of power, improving the quality of life, enhancing educational opportunities, and catalysing economic growth for those living in energy-starved regions.

Furthermore, access to energy is a driving force for gender equality. In many developing countries, women are disproportionately affected by energy poverty, as they are often responsible for household tasks like cooking, which can involve dangerous and polluting fuels. Solar energy can reduce this burden by providing cleaner and safer cooking alternatives, thus empowering women and improving their overall well-being.

2.5 Obstacles to overcome on the path to widespread adoption of solar energy.

Changes to solar energy, on the other hand, are not without their difficulties. Developing countries usually face limitations in terms of the financial resources available for the development of infrastructure, which continues to be a significant hurdle. It is important to make significant initial expenditures in order to construct the necessary solar infrastructure, which includes solar farms, distribution networks, and alternatives for energy storage.

Concerns over grid interconnection and infrastructure combine to provide further obstacles. It is necessary to improve and modernise the energy infrastructure of many developing countries,

which is obsolete, in order to tolerate the swings in electricity supply that are inherent to solar energy. An ambition that is both difficult and expensive to accomplish is ensuring grid stability while simultaneously integrating renewable sources.

The deployment and maintenance of solar energy systems might be made more difficult in these places due to the fact that there is frequently a deficiency of technical experience in these areas. It is absolutely necessary to have a skilled labour force in order to guarantee the long-term viability of solar projects. Another factor that can discourage investment in solar energy is the existence of contradictory legislation, bureaucratic obstacles, and a lack of clear incentives. These obstacles posed by regulations have the potential to hinder growth and innovation within the sector.

Solar energy promotion in underdeveloped countries is not an easy task to do because of the problems that are presented here. There is, however, a ray of optimism due to the fact that technological breakthroughs, legislative initiatives, and the concept of smart cities offer chances to overcome these challenges and usher in a new era of urban development that is both sustainable and resilient. The purpose of this viewpoint post is to provide a full knowledge of the obstacles and opportunities connected with the adoption of solar energy in the context of smart cities within developing nations. This paper goes deeper into these two essential factors.

Nigeria, the most populous nation in Africa, is experiencing a significant energy crisis that hampers its economic progress and diminishes the quality of life for its population. Notwithstanding its extensive stocks of renewable energy resources, such as solar, wind, hydro, and biomass, the country largely depends on fossil fuels, particularly natural gas and oil, for electricity generation. The significant reliance on non-renewable resources has led to environmental deterioration, heightened greenhouse gas emissions, and an inconsistent power supply in both rural and urban areas (Sambo, 2009; Ohunakin et al., 2014). The Nigerian energy sector is marked by frequent power outages, insufficient generation capacity, substandard transmission infrastructure, and elevated prices linked to fossil fuel energy production. According to the International Energy Agency (IEA, 2021), more than 90 million

2.6 Nigeria Energy Landscape

Over 40% of the Nigerian population lacks access to power. This energy shortfall impedes industrial productivity, discourages foreign investment, and intensifies socio-economic disparity. In rural regions, the circumstances are becoming concerning, as power access rates dip below 30%, thereby constraining chances for education, healthcare, and small-scale company development (World Bank, 2022).

Nigeria's geographical and climatic conditions present ample prospects for the advancement of renewable energy. The nation averages solar radiation of 5.5 kWh/m²/day, totalling over 3000 hours of sunshine per year, positioning solar energy as one of its most potential renewable resources (Shaaban & Petinrin, 2014). The potential for wind energy is considerable in the northern regions, where average wind speeds surpass 5.0 m/s at a height of 10 meters. Hydropower resources, particularly small- and medium-scale hydro sites, are dispersed throughout Nigeria's river basins and remain predominantly unexploited (Ohunakin et al., 2014). Moreover, biomass

derived from agricultural wastes and animal waste constitutes a sustainable energy source, especially for off-grid rural applications.

Notwithstanding these benefits, the implementation of renewable energy in Nigeria progresses sluggishly due to various obstacles. Factors include insufficient political will, feeble regulatory frameworks, restricted access to financing, inadequate technical proficiency, and low public awareness (IRENA, 2020). Investors are often deterred by inconsistent energy policies, volatile tariffs, and challenges in securing licenses and approvals. Moreover, the national grid is inadequately prepared to incorporate decentralised renewable energy systems, therefore constraining the potential for distributed generation (Sambo, 2009). Countries that have deliberately invested in renewable energy have experienced substantial advantages in energy accessibility, climate resilience, and employment generation. Kenya's investment in geothermal and solar energy has significantly enhanced rural electrification and stabilised energy prices (IRENA, 2020). These success narratives offer pertinent frameworks for Nigeria to embrace, modify, and expand to realise Sustainable Development Goal 7: cheap and clean energy for all. This study aims to investigate the obstacles impeding the advancement and implementation of renewable energy technologies in Nigeria. The study seeks to enhance the nation's sustainable and inclusive energy future by analysing current obstacles and pinpointing reform prospects. Confronting these difficulties is crucial for attaining energy security, minimising climate change, improving public health, and fostering socio-economic development.

2.7 Assessment of Renewable Energy Capabilities in Nigeria

Nigeria possesses vast renewable energy resources that, if efficiently utilised, may profoundly revolutionise its energy sector, diminish reliance on fossil fuels, and facilitate socio-economic growth. Renewable sources—solar, wind, hydro, and biomass—are naturally and geographically dispersed throughout the country, providing many alternatives for both decentralised and grid-connected applications. The sun energy is likely the most potential renewable resource in Nigeria, given the country's position inside the high sun radiation belt of sub-Saharan Africa. The country averages a solar insolation of 5.5 kWh/m²/day and undergoes approximately 3,000 hours of sunlight each year (Sambo, 2009). This degree of solar radiation renders both photovoltaic (PV) and concentrated solar power (CSP) technologies feasible for energy production, particularly in rural and off-grid regions.

Recent government initiatives, including Nigeria's Solar Power Naija program, seek to capitalise on the capacity to enhance energy accessibility and diminish dependence on diesel generators. The potential for wind energy is primarily located in the northern regions, where wind speeds vary from 4.0 to 5.1 m/s at a height of 10 meters (Sambo, 2009). This range is appropriate for small to medium-scale wind turbines and is adequate for powering community microgrids, irrigation systems, and rural health facilities. Wind mapping studies have highlighted locations in states such as Sokoto, Katsina, and Borno as favourable for pilot wind energy initiatives. Hydropower continues to be an essential component of Nigeria's energy portfolio. The nation possesses an estimated minor hydropower potential over 3,500 MW, distributed across its various rivers and streams (Ohunakin et al., 2014). Although large-scale hydroelectric facilities like Kainji and Shiroro are operational, tiny and mini-hydro systems are attracting interest due to their reduced environmental effects and appropriateness for isolated populations.

Nigeria produces around 144 million tonnes of biomass annually from agricultural residues, forestry by-products, and animal wastes (Shaaban & Petinrin, 2014). These materials can be transformed into biofuels, biogas, and briquettes, providing clean options for cooking, heating, and electricity generation. Notwithstanding these considerable potentials, practical implementation is constrained by infrastructural, regulatory, and financial obstacles that the nation must overcome to achieve a sustainable energy future.

3.0 The Contribution of Solar Energy to Developing Countries

In the worldwide effort to address energy concerns and support sustainable development, particularly in poor countries, solar energy has emerged as a crucial component; it has become a vital actor. In order to have a more positive and environmentally friendly future, it is vital to have a multidimensional understanding of the various aspects of solar energy adoption in these locations.

3.1 The Elimination of Energy availability Through Improvements in Energy Access

There are billions of individuals who are affected by energy poverty, which is a major issue in developing countries. The lack of access to dependable and reasonably priced energy is a problem that affects individuals and entire communities as well. Lack of access to electricity not only makes day-to-day life more difficult in rural and isolated locations, but it also impedes the growth of essential industries like healthcare, education, and economic activity. One of the most persuasive arguments in favour of solar energy is the current demand for increasing access to energy sources. Solar solutions that are off-grid and decentralised, such as solar household systems and mini-grids, are giving communities that were previously without access to electricity the ability to become self-sufficient. For those who live in areas that are lacking in energy, these solutions offer a source of electricity that is both inexpensive and sustainable, which in turn improves the quality of life, expands educational opportunities, and stimulates economic growth.

A further factor that contributes to the advancement of gender equality is the availability of electricity. They are generally responsible for domestic duties such as cooking, which can require fuels that are hazardous and polluting. As a result, women are disproportionately affected by energy poverty in many developing nations. Solar power has the potential to alleviate this burden by offering alternatives to cooking that are both cleaner and safer. This would result in women gaining more power and an overall improvement in their health.

3.3 Environmental Benefits: Addressing Climate Change.

The ecological advantages of solar energy surpass just electricity generation. Developing nations, akin to the global community, are contending with the ramifications of climate change, which encompass increased frequency and intensity of meteorological phenomena, altered precipitation patterns, and agricultural disruptions. By embracing solar energy, these nations aid the worldwide initiative to diminish greenhouse gas emissions and alleviate climate change.

The minimal carbon footprint of solar energy renders it an essential resource in combating global warming. Photovoltaic systems capture solar energy without releasing greenhouse gases, rendering them a sustainable and environmentally benign energy source. By substituting fossil fuels for power generation, solar energy mitigates detrimental air pollutants, enhancing air quality and public health. This shift to cleaner energy corresponds with global climate accords and establishes

a framework for developing nations to diminish their emissions and exemplify responsible energy stewardship.

3.3 Economic Advantages: Employment Generation and Expense Minimisation

The economic advantages of solar energy implementation are dual-faceted. The sector offers substantial prospects for employment generation. The installation, maintenance, and production of solar panels and associated technologies can create job possibilities, especially in areas with significant solar potential. These positions encompass a range of skill levels, from technicians to engineers, enhancing local economies and livelihoods.

Secondly, solar energy presents the opportunity for decreased energy expenses for both individuals and enterprises. As the price of solar technology decreases, electricity produced from solar sources becomes progressively competitive with traditional energy sources. This decrease in energy costs liberates resources that can be redirected to other vital necessities, such as education, healthcare, and infrastructure development. Reduced energy expenses for enterprises also bolster competitiveness and profitability, consequently fostering economic growth and elevating living standards.

3.3.1 Energy Security: Mitigating Reliance on Fossil Fuels

Developing nations frequently depend significantly on imported fossil fuels, rendering their economies vulnerable to fluctuating worldwide oil prices and geopolitical uncertainties. The reliance on fossil fuel imports might result in adverse economic effects and impede overall energy security. Solar energy presents a solution by supplying a local, native, and sustainable power source. By diversifying their energy portfolio with solar power, developing nations can mitigate their susceptibility to foreign energy supply interruptions and price volatility. The deployment of solar energy enhances energy security, stabilises energy availability, and fosters economic resilience and independence.

Additionally, solar energy can be utilised in decentralised systems, like rooftop solar panels and microgrids, enabling small communities to produce their own electricity. The decentralisation of energy production diminishes dependence on centralised power plants and extensive transmission links, hence augmenting energy security and resilience.

In conclusion, solar energy's significance in developing nations extends beyond a mere transition in energy sources; it constitutes a crucial advancement in tackling energy accessibility, environmental sustainability, economic growth, and energy security. Energy poverty, climate change, and economic inequities present concerns that are uniquely addressed by solar energy options. By capitalising on these prospects, developing nations may revolutionise their energy frameworks, promote sustainable development, and provide a more promising, cleaner future for their populations.

4.0 Challenges in Solar Energy Adoption.

Although the advantages of solar energy in developing nations are significant, various obstacles must be addressed to achieve its complete potential. These challenges include financial limitations, obsolete infrastructure, inadequate technical proficiency, and intricate policy and regulatory frameworks.

4.1 Financing: Scarce Financial Resources for Infrastructure Development

A major obstacle to the extensive adoption of solar energy in underdeveloped nations is the restricted availability of financial resources. Establishing the requisite solar infrastructure necessitates significant initial expenditures in solar panels, inverters, energy storage devices, and distribution networks. Although the long-term economic advantages are clear, securing the initial funding to finance such initiatives presents a significant barrier. Government budgets frequently experience constraints, while the private sector may exhibit reluctance to invest owing to perceived risks and uncertainties.

Addressing this financial disparity requires innovative funding strategies. These may encompass public-private partnerships, international development assistance, concessional loans, and the creation of specialised funds for renewable energy initiatives. Implementing efficient finance solutions can enhance the adoption of solar energy infrastructure, rendering it more accessible to a wider demographic and a diverse array of investors.

4.2 Infrastructure and Grid Integration: Obsolete Infrastructure and Grid Unreliability

The current energy infrastructure in numerous developing nations is antiquated and inadequately prepared to handle the fluctuating and decentralised characteristics of solar energy. Solar generation is sporadic, and grid instability may arise if the infrastructure fails to accommodate the variations in power supply. This poses a dual challenge: the modernisation of the electrical grid and the integration of smart grid technologies to facilitate the smooth assimilation of renewable energy sources.

Enhancing infrastructure necessitates considerable money and time. Nonetheless, it is crucial for the efficient incorporation of solar energy into the energy portfolio. The shift to a smart grid, featuring real-time monitoring and control functionalities, can improve grid stability, facilitate efficient energy distribution, and reduce energy losses during transmission.

Microgrid systems are feasible alternatives for distant and off-grid regions, as they can function autonomously or in cooperation with the primary grid. These microgrids provide localised energy generation and distribution, enhancing resilience to external grid disruptions and bolstering energy security.

4.3 Deficiency in Technical Proficiency: Inadequate Training and Knowledge

Solar energy systems necessitate specialised technical proficiency for installation, maintenance, and optimal functioning. Regrettably, numerous developing nations encounter a deficiency of skilled professionals in this domain. Inadequate training and understanding may yield inadequately built and maintained solar installations, resulting in diminished performance, elevated costs, and a shortened system lifespan.

Resolving this issue necessitates investment in training and educational programs for local technicians, engineers, and maintenance staff. By offering extensive training and certification programs, nations may cultivate a proficient workforce capable of assuring the efficient functioning of solar energy systems. This investment in human capital not only fosters the

sustainability of solar initiatives but also generates employment possibilities, so bolstering economic growth.

4.4 Policy and Regulatory Obstacles: Inconsistent Policies and Regulations

Ambiguous and inconsistent policies and regulations can foster an adversarial atmosphere for the deployment of solar energy. Frequent policy alterations, bureaucratic obstacles, and an absence of standardised standards might dissuade investors and impede project development. The lack of clearly defined incentives, subsidies, and feed-in tariffs may further dissuade solar energy ventures.

An extensive and clear regulatory framework is crucial for ensuring clarity and stability in the solar energy sector. Governments ought to formulate and execute supportive policies that provide incentives and subsidies to promote investment in solar initiatives. Regulatory agencies must collaborate with industry stakeholders to establish a conducive climate that promotes project development, safeguards investor interests, and enables a seamless transition to solar energy.

In conclusion, although the potential of solar energy in developing countries is substantial, these governments must confront a range of intricate problems to fully capitalise on its benefits. Addressing financial obstacles, upgrading infrastructure, cultivating technical proficiency, and establishing conducive policy frameworks are essential measures in the pursuit of sustainable and resilient solar energy implementation. Confronting these problems will expedite the shift to clean and dependable energy sources, while also fostering economic growth and enhancing the quality of life for numerous citizens in emerging areas.

5.0 Impediments to Solar Energy Adoption.

Despite the considerable benefits of solar energy in developing countries, numerous challenges must be overcome to realise its full potential. The problems encompass financial constraints, outdated infrastructure, insufficient technical expertise, and complex legislative and regulatory frameworks.

5.1 Financing: Inadequate Financial Resources for Infrastructure Development

A significant barrier to the widespread implementation of solar energy in developing countries is the limited access to financial resources. Establishing the necessary solar infrastructure requires substantial initial investments in solar panels, inverters, energy storage systems, and distribution networks. Despite the evident long-term economic benefits, obtaining the initial capital to support such ventures constitutes a considerable obstacle. Government budgets often face limitations, whilst the private sector may hesitate to invest due to perceived risks and uncertainties. Mitigating this financial inequity necessitates inventive funding approaches. These may include public-private partnerships, international development aid, concessional loans, and the establishment of specialised funds for renewable energy projects. Implementing effective financial solutions can facilitate the adoption of solar energy infrastructure, making it more accessible to a broader demography and a varied range of investors.

5.2 Infrastructure and Grid Integration: Outdated Infrastructure and Grid Instability

The existing energy infrastructure in many developing countries is obsolete and insufficiently equipped to manage the variable and decentralised nature of solar energy. Solar energy is

intermittent, and grid instability may occur if the infrastructure cannot adapt to fluctuations in power supply.

This presents a twofold challenge: the upgrading of the electrical infrastructure and the integration of smart grid technologies to enable the seamless incorporation of renewable energy sources. Improving infrastructure requires substantial financial resources and time. However, it is essential for the effective integration of solar energy into the energy portfolio. The transition to a smart grid, equipped with real-time monitoring and control capabilities, can enhance grid stability, enable efficient energy distribution, and minimise energy losses during transmission.

Microgrid systems are viable alternatives for remote and off-grid areas, as they can operate independently or in conjunction with the main grid. These microgrids provide localised energy generation and distribution, improving resilience against external grid disturbances and strengthening energy security.

5.3 Deficiency in Technical Proficiency: Insufficient Training and Knowledge

Solar energy systems require specialist technical expertise for installation, maintenance, and maximum performance. Unfortunately, many emerging countries face a shortage of trained workers in this field. Insufficient training and comprehension may lead to poorly constructed and maintained solar installations, resulting in reduced performance, increased expenses, and a decreased system lifespan.

Addressing this issue requires investment in training and educational initiatives for local technicians, engineers, and maintenance personnel. Nations can develop a skilled workforce capable of ensuring the efficient operation of solar energy systems by providing comprehensive training and certification programs. This investment in human capital not only promotes the sustainability of solar ventures but also creates employment opportunities, hence enhancing economic growth.

5.4 Policy and Regulatory Barriers: Inconsistent Policies and Regulations

Ambiguous and contradictory policies and regulations might create a hostile environment for the implementation of solar energy. Frequent legislative changes, bureaucratic hurdles, and a lack of defined criteria may deter investors and hinder project advancement. The absence of explicitly specified incentives, subsidies, and feed-in tariffs may further deter solar energy initiatives.

A comprehensive and transparent regulatory framework is essential for providing clarity and stability in the solar energy sector. Governments should develop and implement supportive policies that offer incentives and subsidies to encourage investment in solar projects. Regulatory agencies must cooperate with industry stakeholders to create an environment that fosters project development, protects investment interests, and facilitates a smooth transition to solar energy.

In conclusion, while the potential of solar energy in developing nations is significant, these governments must address a variety of complex challenges to properly harness its advantages. Mitigating financial barriers, enhancing infrastructure, developing technical expertise, and instituting favourable legislative frameworks are critical actions for achieving sustainable and resilient solar energy deployment. Addressing these issues can accelerate the transition to clean

and reliable energy sources, while simultaneously promoting economic development and improving the quality of life for many individuals in developing regions.

6.0 Case Studies

The practical application of solar energy adoption and smart city programs in several developing nations offers significant insights into the problems, opportunities, and policy strategies that have proven beneficial in promoting sustainable urban development. We examine case examples from Nigeria, India, Rwanda, and Brazil, emphasising significant initiatives and their effects.

6.1 Nigeria: Examples include a study on using solar PV to replace diesel generators in Lagos, an analysis of solar energy integration into a rural community grid in the Niger Delta, and a case study of the Solar Sister program that empowers women entrepreneurs. Other studies examine the overall solar potential, affordability, and policy frameworks in Nigeria.

Case studies and research on Nigerian solar programs

- *Solar PV for replacing diesel generators:* A case study focusing on Lagos, Nigeria, demonstrates how solar PV systems can reduce or eliminate the use of diesel generators, leading to significant cost savings over the project's lifetime.
- *Rural electrification and grid integration:* A study in the Umuezerokam community in the Niger Delta analyzes the feasibility and performance of integrating solar energy into the national grid to improve electricity supply in rural areas.
- *Solar Sister program:* This case study examines the activities of the Solar Sister program in Nigeria, which focuses on training and supporting women entrepreneurs in the clean energy sector.
- *Solar energy potential and development:* This research provides an overview of Nigeria's abundant solar energy potential and outlines a roadmap for developing it sustainably, acknowledging the challenges and opportunities involved.
- *Policy review and market analysis:* Several papers provide reviews of solar energy policies and their impact on market development, including analyses of the current status, affordability, and challenges of solar PV electrification in Nigeria.
- *Profitability and business strategies:* A case study explores the profitability strategies used by solar energy businesses in Lagos, Nigeria.

6.2 India - The Solar Cities Initiative (Ministry of New and Renewable Energy, Government of India, "Solar Cities," mnre.gov.in, The Energy and Resources Institute (TERI), "Solar Cities in India," teriin.org)

The Solar Cities program in India is a holistic endeavour aimed at advancing solar energy and sustainability in urban environments. Initiated by the Ministry of New and Renewable Energy, the initiative seeks to convert designated communities into "Solar Cities" by the incorporation of solar technology into multiple facets of urban living.

Principal Characteristics and Effects: The program promotes the installation of solar panels on rooftops to produce sustainable energy for residences, enterprises, and public facilities.

- **Solar Street Lighting:** Solar-powered streetlights diminish energy usage and improve safety in

metropolitan environments.

- **Renewable Energy Awareness:** Public awareness initiatives and educational activities enlighten citizens regarding the advantages of renewable energy and sustainable practices.
- **Waste-to-Energy Initiatives:** Certain Solar Cities have executed waste-to-energy initiatives, transforming organic waste into biogas and power.
- The program incorporates solar energy solutions into urban design, facilitating the adoption of sustainable practices in transportation, building, and waste management by communities. The Solar Cities Initiative illustrates India's dedication to promoting sustainable urban development via solar implementation and clean energy initiatives. Through the utilisation of public awareness and governmental backing, the program has achieved significant advancements in converting cities into centres of renewable energy.

6.3 Rwanda - The Kigali Innovation City Initiative (Rwanda Development Board, "Kigali Innovation City," *rdw.rw*, GreenBiz "Africa's Silicon Valley: Rwanda's Ambitious Plan for Smart Cities"*greenbiz.com*)

The Kigali Innovation City project in Rwanda is an ambitious endeavour aimed at establishing a knowledge-based economy and fostering sustainable development. It integrates renewable energy, smart city principles, and digital infrastructure.

Principal Characteristics and Effects:

The project emphasises sustainable construction and green building approaches to minimise energy use.

- *Solar Energy Integration:* Photovoltaic panels are affixed to structures to produce sustainable electricity for municipal functions.
- *Smart Mobility:* The initiative encompasses the establishment of a public transit network and infrastructure for electric automobiles. Kigali Innovation City emphasises digital connectivity and digitalisation, fostering technology-driven innovation. The project seeks to establish Rwanda as a technological centre in Africa, highlighting the capacity of solar energy and smart city initiatives to foster economic growth and sustainable development.

7.0 Opportunities and Prospective Outlook

The prospects offered by solar energy implementation in developing nations are extensive and possess the capacity to induce disruptive alterations throughout several sectors. The future prospects for solar energy in these areas are favourable, encompassing rural electrification, energy for productive applications, the generation of green employment, and technology advancements that could transform energy distribution.

8.0 Rural Electrification: Expanding Solar Accessibility to Isolated Regions

Rural electrification is a critical objective in numerous developing nations. Solar energy is a viable means to enhance electricity accessibility in remote and neglected areas. Off-grid and decentralised solar solutions, such as solar household systems and mini-grids, are significantly impacting communities by delivering reliable and sustainable power to those previously without access. These programs enhance the quality of life in rural regions by facilitating illumination, communication, and access to information, while also stimulating economic activities. They facilitate agricultural practices, improve education and healthcare facilities, and support small-scale companies, thereby narrowing the urban-rural development disparity.

8.1 Energy for Productive Applications: Assisting Agriculture and Small Enterprises

The promise of solar energy transcends mere electrification. It can be utilised to bolster agriculture and small enterprises, especially in rural regions. Solar-powered irrigation systems facilitate efficient crop watering for farmers, hence enhancing agricultural output and income. Solar cold storage facilities prolong the shelf life of agricultural products, minimising post-harvest losses. Moreover, small and medium-sized firms (SMEs) can leverage solar energy solutions, which provide dependable and economical power sources. Solar water pumps might be essential for enterprises in the food processing sector, enabling them to enhance operational efficiency and decrease energy expenditures. These applications are essential for economic development and employment generation in emerging regions.

8.2 Green Employment: Prospects for Employment and Entrepreneurship

The solar energy sector offers significant prospects for employment and entrepreneurship. As solar technology becomes increasingly economical and attainable, the demand for proficient individuals in solar installation, maintenance, and manufacture is escalating. This labour increase fosters economic progress and enhances livelihoods in developing nations.

Furthermore, the solar sector promotes entrepreneurship and domestic production, enhancing economic self-sufficiency. Small-scale solar firms, including solar panel assembly or distribution, can prosper and cater to local markets. Moreover, solar-powered micro-enterprises, including phone charging stations, generate economic prospects in off-grid regions.

8.3 Technological Innovations: The Impact of AI and Blockchain on Energy Distribution

The advancement of solar energy in emerging nations is intricately linked to technological innovations. Artificial intelligence (AI) and blockchain technology are set to transform energy distribution and management. This will be accomplished through the following:

- 1) *Artificial Intelligence for Energy Optimisation:* AI systems can enhance energy generation, distribution, and consumption efficiency. Machine learning algorithms can forecast energy demand and align it with solar generation, ensuring optimal electricity utilisation. This technology is essential for smart grids and microgrids, particularly in regions with sporadic energy sources.
- 2) *Blockchain for Decentralised Energy Trading:* Blockchain technology enables peer-to-peer energy trading, allowing individuals and enterprises to directly buy and sell surplus solar-generated electricity. The notion of decentralised energy trading fosters energy self-sufficiency and bolsters energy security in regions with unstable grid connections. The amalgamation of AI and blockchain in solar energy management enhances customer empowerment, fortifies grid resilience, and mitigates energy losses during distribution. It additionally facilitates the shift to clean and sustainable energy sources.

The future prospects for solar energy in developing nations are marked by a transition towards equitable and sustainable development. It has prospects for electrifying rural regions, improving agricultural efficiency, generating green employment, and implementing advanced technology to optimise energy delivery. These advancements enhance community well-being while fortifying the resilience and economic sustainability of these places, so securing a more promising and sustainable future.

9.0 Additional surveys and research

Renewable energy initiatives, especially in rural areas of developing countries, are essential for meeting global energy demands and fostering sustainability. The acceptance and long-term sustainability of such programs rely on a complex interplay of elements. This review article examines a number of studies from a systems thinking perspective to elucidate this complex subject. By comprehending these dynamics, we intend to offer significant insights into how renewable energy efforts might be more easily adopted and maintained within various contexts.

9.1 Principal study domains and subjects pertaining to solar energy deployment in developing nations

Topic 1: Sustainability in solar energy projects (Garraín & Lechón, 2023):

Findings: A sustainability study mitigates adverse effects on environmental, social, and economic dimensions. Both LCA and MRIO possess inherent limitations. - IO analysis can yield varying outcomes and influence sustainability objectives.

Conclusions: Scientific frameworks such as FISA are crucial for decision-makers. - Precise objectives, parameters, and metrics are essential. - Solar energy is essential for achieving sustainable development objectives.

Topic 2: Solar energy's contribution to sustainable development objectives (Obaideen et al., 2021).

Findings: Solar energy facilitates the achievement of SDGs by reducing carbon emissions, enhancing power capacity, lowering costs, and providing home energy. - The MBR Solar Park in Dubai is of considerable importance. The park evaluates diverse solar technology; Conforms to Dubai's 2050 strategy for renewable energy.

Conclusion: Solar energy is crucial for a sustainable future. The MBR Solar Park demonstrates the viability of ambitious solar initiatives.

Topic 3: The environmental performance of solar energy systems varies, with thin-film CIS exhibiting reduced impacts (Milousi et al., 2019).

Findings: The factors of efficiency, area, and cost vary among photovoltaic systems. - Flat plate methods are economically viable in specific climates.

Conclusions: Diverse photovoltaic technologies provide comparable energy output and emissions mitigation. - Flat plate methods are economically viable in certain climates.

Topic 4: The capacity of solar energy to mitigate emissions (Shahsavari et al., 2018)

Findings: Proposals to mitigate obstacles, encompassing subsidies, feed-in tariffs, and loans; International assistance, tax incentives, and proficient labour forces are crucial; Carbon price can incentivise the adoption of clean energy; Promoting awareness of environmental consequences is essential.

Conclusion: Constructive methodologies and political tactics are essential for the advancement of solar energy; Subsidies, feed-in tariffs, and loans promote renewable energy; Global collaboration and financial support are necessary; Tax incentives and carbon pricing facilitate the advancement of sustainable energy; Competent labour forces and research and development incentives are essential for the progression of solar technology; Promoting awareness of environmental issues is essential.

Topic 5: Solar Energy and Rural Development in Developing Countries (Ramakumar, 1977)

Findings: Advocate for a slow, incremental implementation of energy solutions in rural regions; Employ "intermediate technology" that corresponds with the economic constraints of poverty; Create rural energy centres to address fundamental needs and educational requirements; Establish local government initiatives to facilitate rural development; Mitigate rural unemployment by establishing energy centres.

Conclusion: Rural development should emphasise the incremental adoption of energy resources; Technology ought to be appropriate for societies with a surplus of workers; Rural energy centres can provide employment and enhance rural living conditions; Robust rural development is essential for comprehensive societal welfare.

Topic 6: Urban Design for a Sustainable Energy Future (Vandevyvere & Stremke, 2012)

Findings: Minimising energy use is a primary goal in the shift to renewable resources; Urban characteristics significantly influence the reduction of demand; The optimisation of energy flows is crucial for exergy enhancement, and; Renewable energy ought to satisfy the residual demand across many scales.

Conclusion: Decreasing energy consumption is a fundamental measure for achieving a green energy future; Urban morphology and exergy optimisation are essential factors; Renewable energy ought to supplement residual energy requirements across various sizes, and; Interdisciplinary research and application are essential for sustainable urban development.

Topic 7: The influence of socio-cultural factors on solar power adoption (Lin & Kaewkhunok, 2021)

Findings: The age of household heads positively affects the adoption of solar power. - Elderly household heads exhibit a greater propensity to utilise solar technology; Household income affects adoption rates; higher-income households exhibit greater adoption; Elevated educational attainment of household heads favourably influences adoption; Access to financing positively impacts adoption; Rural households exhibit a higher propensity to adopt solar power compared to their urban counterparts; Households lacking grid connection are more inclined to adopt solar energy; Adoption differs by developmental region, and; Adoption differs among ecological regions, and; Ethnic significantly influences adoption.

Conclusion: Socio-cultural issues, and inter-ethnic disputes, substantially influence the adoption of solar power technologies; Policymakers must take into account socio-cultural issues and advocate for equality via education and institutions to guarantee equitable access to contemporary energy technology.

Topic 8: Social acceptability of solar energy in Finland (Hai, 2019).

Findings: It is categorised into four levels of willingness to adopt: active willingness, unconditional willingness, conditional willingness, and unwillingness; Various client groupings are delineated according to these states, and; Social acceptance is classified into adoption, acceptance in principle, rejection, and opposition. Factors influencing adoption to promote uptake across diverse client segments.

Conclusions: To expedite the adoption of solar energy in Finland, it is crucial to address the varying levels of willingness and client segments with customised information and assistance; and; Policies and strategies must take into account both pre-adoption and post-adoption phases.

Topic 9: Causal Loop Diagrams Pertaining to the Acceptance of Renewable Energy Source Projects (González et al., 2016)

Findings: This section displays five causal-loop diagrams illustrating the primary factors that determine the sustainability and acceptance of renewable energy system projects within rural areas. The graphics were created within the confines of five distinct livelihood capitals: social, human, physical, natural, and financial.

Conclusion: Comprehending the intricate relationships among many livelihood capitals is essential for the success of renewable energy initiatives in rural communities. Interventions must be comprehensive, culturally attuned, and account for various characteristics of the community. Engaging the community, delivering education, and guaranteeing access to financial services are essential for project sustainability.

Topic 8.1: Social Capital -Positive Relationship

Findings: Networks and trust affect community adoption of renewable energy system projects.

Conclusion: Community acceptance is contingent upon social capital.

Topic8.2: Human Capital: Access to superior education and technology augments human capital. Energy deficiency impairs critical services.

Conclusion: Access to education and technology is essential.

Topic 8.3: Physical Capital

Findings: Fundamental infrastructure is essential for education, healthcare, and economic creation. Energy accessibility boosts community appeal.

Conclusion: Infrastructure is crucial for development and project approval.

Topic 8.4: Natural Capital - Environmental Quality.

Findings: Renewable Energy System initiatives may negatively impact the natural environment. Both direct and indirect effects must be taken into account.

Conclusion: Renewable energy sources can impact the environment, hence affecting public acceptance.

Topic8.5: Monetary Resources

Findings: Monetary resources can yield revenue; but, access to financial services is essential. Payment structures ought to mitigate risk.

Conclusion: Financial resources and credit accessibility are essential for project success.

9.0 Conclusion

Developing nations encounter unique obstacles in adopting solar energy; nonetheless, the potential for sustainable growth and advancement is substantial. The shift to clean energy sources becomes more attainable as smart cities play a crucial role in this transition. Technological advancements, the enactment of supportive legislation, and international collaboration have highlighted the promise of solar energy in underdeveloped countries. By adeptly tackling these issues and seizing

the available opportunities, these nations are positioned to spearhead a future that is both more sustainable and energy-secure.

Principal Outcome of this study include:

- 1) Energy Transition in Developing Nations: Developing countries possess the opportunity to bypass traditional energy infrastructures and directly adopt renewable sources such as solar, thereby providing sustainable and reliable power for their inhabitants.
- 2) The implementation of solar energy in these places enhances environmental sustainability while concurrently fostering economic growth, generating employment opportunities, and promoting social advancement through improved access to key services.
- 3) The creation of smart cities serves as a catalyst, promoting innovation and efficiency while enhancing the effectiveness and accessibility of solar energy integration.
- 4) Technology and infrastructure Advancements: Accelerated technology innovation and infrastructure enhancement are propelling solar energy usage, decreasing costs, and enhancing energy accessibility for isolated populations.
- 5) Supportive policies and international cooperation are crucial facilitators of solar energy expansion, offering vital frameworks and investment prospects.
- 6) Resilience and Energy Security: Solar energy improves energy resilience, mitigating susceptibility to supply disruptions and strengthening energy security.

These findings emphasise the significant potential of solar energy in developing nations, where the integration of technology advancement, smart city initiatives, favourable regulations, and international collaboration facilitates a more sustainable and promising future. In light of urgent energy and environmental issues, these nations are positioned to lead in the development of a robust, secure, and sustainable global energy framework.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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A SYSTEMATIC REVIEW OF VALUE CREATION AND COMPETITIVE ADVANTAGE VIA COLLABORATION BETWEEN TERTIARY INSTITUTIONS AND INDUSTRY

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Abstract

The collaboration between higher education institutions and businesses is becoming increasingly vital due to the intensifying competitive landscape, shaped by fierce global rivalry, swift technical advancements, and abbreviated product life cycles. This essay analyses many case studies and pertinent academic literature to get insight into the existing connection between corporations and higher institutions. The method applied in this paper is based on a literature assessment of Tertiary institution-Industry Partnerships, drawn from indexed sources, and focused on case-based experiences that provide practical feedback. Tertiary institution-industry knowledge transfer considerably enhances the quality, productivity, and economic worth of firms. The absence of regulatory mechanisms and efficient communication pathways significantly undermines collaboration. Essential collaborative elements that enhance connections were gathered and examined to improve mitigation measures. The restricted availability of case studies detailing operative enhancements resulting from policy adjustments impedes the efficacy of the findings. The article examines the partnership between the tertiary institution and industry through case studies, emphasising value creation and the attainment of competitive advantage via collaboration.

Research has demonstrated the advantages of cooperation between industry and academia for students, faculty, and industry stakeholders. Nonetheless, numerous problems exist in forming such collaborations, which, if unaddressed, may lead to either the failure of the collaboration or a negative experience for the concerned parties. This study begins by summarising the advantages

of such cooperation, as evidenced by the authors' experience and a literature review. This is succeeded by the identification of a series of potential issues that may develop. This paper addresses issues that may be recognisable to seasoned collaborators, hence it is aimed at individuals who are new to cooperation or plan to engage in such endeavours in the future. This paper primarily focusses on challenges pertinent to partnerships in computers and software engineering.

1.0 INTRODUCTION

The collaboration between tertiary institutions and industry in Europe exhibits a varied environment. The collaboration between enterprises and tertiary institutions is a recent and emerging phenomena (Unger et al., 2018; Jarábková, Chreneková, and Roháčiková, 2019). Companies and academic institutions differ in their organisational structures and cultures, resulting in divergent perspectives on technology management. There exists considerable potential for enhanced and more vigorous collaboration between higher education institutions and enterprises; yet, challenges persist regarding mutual trust and comprehension of operations on both sides (Pařová, Czaja and Vejačka, 2018; Roud and Vlasova, 2018). Nonetheless, models or theoretical frameworks for comprehending the involvement of customers and other stakeholders in enterprises' collaborative value co-creation activities (Frow et al., 2015) remain inadequate. Recent research has predominantly focused on case studies of large multinational corporations and prominent tertiary institutions (Edmondson, 2012). Limited research has examined the partnership among higher education institutions, small and medium-sized enterprises, and non-governmental organisations.

Higher education institutions and corporations get advantages from collaboration, which facilitates the transfer and dissemination of knowledge, hence fostering the establishment of enduring partnerships (Guan and Zhao, 2013). The significance of collaboration among science, information, and technology in the innovation process is increasingly emphasised (Rebelo, Santos, and Silva, 2015; Wu and Chiu, 2015; Unger et al., 2018), and in the advanced industrial economy, there exists a robust integration of science and technology systems (Bravi, Murmura, and Santos, 2018). Collaboration is emerging as a formidable source of competitive advantage. Nonetheless, the process of knowledge transfer has several deficiencies, particularly with communication and collaboration between tertiary institutions and corporations, which adversely affects their innovative ability and consequently undermines successful connections. Key factors exist within the determinants of interaction that, when identified and effectively addressed, will mitigate certain barriers and enhance the management of collaboration between tertiary institutions and enterprises, rendering it more profitable and a source of value for both parties and society at large. The objective of this study is to examine, identify, and analyse the significance of critical concerns related to the interaction between higher education institutions and industry, as well as to address the consequences of overlooked elements. The paper initially examines prevalent tactics employed in the interaction between academic institutions and industry, emphasising the advantages that such partnerships might yield. The subsequent section emphasises the significance of innovation in attaining sustainable competitive advantage within the sector and elucidates why higher schools serve as ideal partners in realising these objectives. The subsequent two parts delineate the achievements of partnerships and highlight significant restrictions that impede the success and future collaboration between industry and educational institutions.

2. IMPORTANCE OF TERTIARY INSTITUTION-INDUSTRY COLLABORATION

Numerous studies have been undertaken in the previous decade regarding the advantages of Industry-Academic Collaboration. Such cooperation are regarded as mutually advantageous for stakeholders in both organisations. Academic institutions offer several advantages for both students and teachers engaged in these collaborations. The subsequent section presents a sampling of these advantages:

2.1 Possible Advantages for Students

- *Extracurricular education.* Students engaged in collaborative projects are anticipated to acquire industry practices and new technologies that may not be included in the curriculum. This empowers these students to confront unexpected situations with assurance and bravery.
- *Grants and financial allowances.* As graduate tuition fees increase nationwide, students want research assistantships more than ever. The relationship between industry and academia finances research, subsequently facilitating scholarships for students through stipends or tuition exemptions.
- *Practical experience in real-world projects and environments.* Students are required to engage in projects throughout their curriculum, particularly in technological degrees. However, students frequently engage in minor projects within a limited scope, usually working independently or with one other individual. Upon graduation and subsequent employment in the business, these students are often daunted by the scale of the projects they are tasked with. The connection between industry and academia offers students the chance to engage in large-scale projects with substantial teams, closely resembling the challenges they will encounter post-graduation. Furthermore, industrial projects are generally linked to strict timeframes, and students engaged in these projects acquire the ability to meet these constraints.
- *Enhance employment opportunities post-graduation.* A student engaged in collaborative projects is typically acquainted with industry culture, values quality, and demonstrates a willingness to acquire new knowledge to remain informed about technological and environmental modifications. The student will be a valuable addition to any employer. Students are increasingly employed by the industry that sponsors the collaboration.
- *Enhanced recognition of quality.* Students generally fail to realise the importance of quality in the final output of their class projects. Software quality is crucial for industrial projects and often undergoes multiple testing phases to eradicate mistakes. Students engaged in collaborative projects must adhere to same quality assurance standards, resulting in a heightened understanding of software quality.

2.2 Possible Advantage for Faculty

- *Facilitator for research and funding opportunities.* Instructing a full course load frequently precludes academics from allocating sufficient time for research activities. In these instances, professors must purchase a course release or obtain summer support, typically financed through external funding sources. The collaborative initiatives allocate funding accordingly. The ensuing research may provide artefacts such as journal publications or conference presentations.
- *Understanding of industry standards.* There frequently exists a disparity between academic and industry practices. Faculty engaged in industrial-academic collaborations can comprehend industry procedures. This facilitates their examination and analysis of the distinctions between

industry and academic approaches. The study assists professors and students in comprehending the advantages and disadvantages of both approaches, facilitating enhancements in both.

- *Enhanced curriculum.* The faculty's newly acquired research knowledge from joint activities is conveyed to students via modifications in the course content. This procedure ensures the academic curriculum remains relevant and does not become obsolete.
- **Access to specialised industry knowledge.** Small colleges typically have a limited number of faculty members in each department. Faculty members frequently encounter challenges in identifying colleagues for collaboration. The partnership between industry and academia presents this potential.

2.3 Prospective Advantage to Industry

- *Access to supplementary personnel.* A cooperation team often comprises several industry professionals, a few faculty members, and multiple students. Consequently, the industry acquires numerous personnel without the necessity of formally hiring any of them. The responsibility of recruiting competent students lies with the faculty, as the industry's financial support is directed at research endeavours rather than individual students. Consequently, the industry acquires proficient people without the necessity of doing a search and interview process. Furthermore, students engaged in these initiatives are supervised by industry professionals, offering insight into their potential as future full-time employees.
- *Access to faculty proficiency.* Certain organisations lack a dedicated research department and may not access advanced research that could provide a competitive advantage. In some instances, the academics participating in the collaborative endeavour offers the research to the industry at a minimal cost.
- *Proprietorship of the completed product.* The industry, in addition to acquiring experience and more personnel, typically obtains the copyright and patent for the completed product.

This section has illustrated the numerous advantages of industry-academic cooperation. Nevertheless, it also highlights several problems and issues encountered by individuals engaged in such collaborative endeavours, which are seldom addressed in the literature. Subsequent sections will address several lesser-discussed problems encountered in industry-academic relationships.

2.4 Issues and Challenges

The advantages outlined in the preceding section are so alluring that stakeholders in both industry and academia are eager to seize any opportunity for partnership that presents itself. Nonetheless, some concerns and challenges accompany such collaboration, which one must recognise to enhance the effectiveness of this partnership for both organisations. The themes and challenges addressed in the subsequent section reflect almost a decade of collaborative experience among the writers and their colleagues across various industries, ranging from small local enterprises to huge multinational organisations spanning multiple continents. This document will address finance, sensitivity, enrolment, and technological challenges in detail in the subsequent paragraphs.

2.5 Changes in the technology market

The late 1990s dot-com bust led to a gradual decline in both student interest in computing education and the availability of research and development funding from the computing sector. The issues were exacerbated by the tragedy of September 11 and the subsequent stock market

collapse. Industries began to economise and were compelled to operate within a significantly reduced budget, thereby leading to a reduction in their research and development expenditure. Furthermore, parents of students expressed heightened anxiety regarding their support for their children's education and the optimal return on their educational investment. Consequently, the following patterns have emerged;

- *Insufficient student interest.* Enrolment in undergraduate computer science and associated programs in the United States has experienced a significant fall. An analysis of survey results from the Higher Education Research Institute at the University of California, Los Angeles, indicates that in 2000, 3.7% of incoming freshmen intended to study Computer Science; in 2002, this figure decreased to 2.2%; and in 2004, it further declined to 1.4%. This represents a 60% decrease over the four-year period from Autumn 2000 to 2004. A comparable tendency is observed in other computer science and engineering departments as well.

Several factors contributing to this reduction include:

- a) decrease in the information technology sector
 - b) augmentation of outsourcing
 - c) the erroneous belief among entering students that Computer Science and Software Engineering predominantly emphasise programming and web design
 - d) Incoming students concentrate on the current job market, which may drastically change in four years.
 - e) Student employees constitute a transitional labour force. Students transition in and out of projects for numerous reasons, including graduation, institution or program transfers, and shifts across research projects. The decrease in enrolment hinders the continuity of student employees for collaborative initiatives, particularly in smaller programs.
- *Insufficient funds.* Recent news reports indicate that funding from DARPA (Defence Advanced Research Projects Agency) for university researchers in computer science has decreased from \$214 million to \$123 million between 2001 and 2004. The Pentagon's budget request amounts to \$419.3 billion. In the upcoming year, approximately \$10.5 million will be allocated to fundamental research, applied research, and advanced technology development, reflecting a 20% decrease from the previous year. The Bush Administration has solicited \$132.2 billion in government Research and Development (R&D) funding for FY2006. Per the request, funding for federal research (including basic and applied) will decrease from \$55.2 billion to \$54.8, a 0.6% decrease. Moreover, several factors such as diminishing government funding, offshore outsourcing, mergers and acquisitions, and budgetary constraints within the business have led to a tendency of reducing discretionary expenditure, resulting in a decline in research investment within the industry. A new analysis indicates that academic-research funding from industry decreased by 1.1% to \$2.16 billion, marking the second consecutive decline following a 40-year period of consistent growth.
 - *Corporate amalgamations.* There has been a rise in M&A (Mergers and Acquisitions) activity in recent years, particularly among software companies. According to the latest data from Mergerstat5, the amount of US and US cross-border M&A transactions rose by 25%, increasing from 8,232 to 10,296 in 2004. Numerous factors motivate a corporation to engage in mergers and acquisitions. The rationale may pertain to expenses, cost reductions, market dominance, and the eradication of competitors or the acquisition of novel technology. Regardless of the rationale, a degree of risk and uncertainty is invariably

there. The business culture and research priorities of the new firm may evolve, thereby complicating collaborative endeavours. The managers may be assigned the responsibility of executing the new corporate policy. Management positions may experience a higher percentage of job losses compared to employees. The job loss may partially result from managers being assigned the implementation of new corporate policies with which they may disagree. The departure of collaborators, typically of managerial status and primarily valued for their financial decision-making authority, will adversely impact the partnership. Moreover, a successful and enduring collaboration necessitates a champion inside both organisations.

In academia, the Principal Investigator (PI) typically fulfils this job, while in industry, it is usually assumed by a technical manager and/or a business manager. M&A may lead to the turnover of the project advocate within the industry, thereby undermining the relationship.

- *Contracts necessitating citizenship due to sensitivity.* Nearly fifty percent of the students, and in some instances even more, engaged in graduate study hold student visas, which creates significant challenges in identifying people eligible to participate in initiatives that necessitate U.S. citizenship. Denizen. Students engaged in industry-academic collaboration projects are generally regarded as the primary candidates for employment inside the sector. Regrettably, post-9/11, an increasing number of enterprises are amending their policies to mandate that students engaged in projects must be U.S. citizens or permanent residents, or so-called "students without work visa complications." The main rationale for this policy change is the manner in which the United States government has, following 9/11, complicated the process for foreign people to get a work visa. Furthermore, amidst the ongoing conflict, there is an augmented necessity for advancements in defence technology, resulting in greater funding for defense-related initiatives, which are highly sensitive and necessitate citizenship.

2.6 Technical Difficulties

Several technological challenges must be considered when establishing an industry-academic collaboration in software engineering. The majority of organisations have been engaged in software development for a lengthy duration, and most have instituted their own software development processes. Recent advancements in software engineering and the introduction of novel approaches and processes at the university may create competing interests between academic and business relationships. The academic partners want to integrate the most advanced techniques into the industry, many of which have not been evaluated in real-world projects. The industry partners are understandably cautious about this strategy, as they have achieved considerable success with their current methods and are reluctant to disrupt established processes that may yield adverse outcomes. Furthermore, the industry partners are apprehensive about permitting individuals who are not regular employees of the organisation to access the company's intranet or sensitive organisational data. The following elaborates on these concerns in depth;

- *Principles of Software Engineering versus temporal limitations.* In collaborative projects involving software application development, students adhere to the software engineering principles acquired during their study. They are instructed on the significance of allocating sufficient time for requirements collecting, analysis, and design to ensure the effective development of an application. Consequently, in the initial stages of the collaboration, the academic partner produces various software artefacts, including the software requirements specification and the software design specification. However, if the industry partner prioritises a functional product, these artefacts may appear less valuable than anticipated. This may result

in dissatisfaction among industry partners with the project's progress. To address this, the academic partner may be compelled to expedite the first phases of the development cycle, perhaps leading to a diminished quality output and contradicting the principles taught in the students' curricula.

- *Comparison of industry best practices and academic best practices.* The collaborative projects enable bidirectional communication between industry and academia, thereby bridging the divide between industrial practices and research methodologies. A significant problem in this domain, as previously mentioned, is the integration of best practices in the software development process (e.g., personal and team software processes, or other so-called "non-productive" activities) within the industry. Conversely, companies often embrace academic techniques and customise them to suit their own organisational needs; at times, these tailored practices enhance the original methodology's efficiency, so rendering them more applicable to real-world scenarios. As academicians, we should embrace these customised techniques and reintegrate them into the classroom. Regrettably, at times, some academics are not keen to get knowledge from our industry collaborators. Without the adaptation of academic best practices by industry and the comprehension of industry best practices by academic researchers, advancements in software engineering methodology are unattainable.
- *Software Compatibility/Proprietorship.* Certain software initiatives need the installation of the cooperating industry's software on university computers. This occasionally conflicts with the current infrastructure of the university's computing facilities. This presents challenges for the development team, necessitating the expenditure of important project time to identify and rectify these incompatibility issues, which are frequently time-consuming and may require approval from other departments that may not be cooperative. Furthermore, the creation of an application for industry partners often necessitates acquiring private data and information. This necessitates securing approvals from several levels and departments inside the organisation, resulting in significant project delays.
- *Collaborative initiative within the production process.* A collaborative project may entail creating a supplementary component for the company's software within the production line. In these instances, it is imperative to ensure that deadlines are observed with greater rigour, as any delay in the component's supply will result in a postponement of the complete software's delivery or shipping. Any delay in its delivery may incur millions of dollars in losses for the sponsoring company. This requirement presents a barrier because to the misalignment of the industry and academic calendars. The academic calendar includes extended breaks. Graduate student workers may receive a one-week break for Thanksgiving and for the spring, as well as a four-week hiatus in December. However, the business often allows no more than two days off for Thanksgiving or Christmas. Should the shipment date coincide with any of these dates, it becomes challenging for the academic colleagues to adhere to the deadline. Any postponement will adversely affect future joint endeavours with the specific industry. Furthermore, by engaging in the production line, the academic partner inadvertently becomes entangled with matters about marketing timelines, product quality, pricing, maintenance, and delivery.
- *IT security Challenges/firewall.* Most collaborative initiatives entail the development of a software application. As prototypes of the product are developed, it becomes essential to provide them to the customer for testing and refining of the requirements. To enable this, either consumers must possess remote access to the university computers for prototype testing, or academic colleagues must have remote access to customers' computers for installation and

maintenance of the prototype, particularly when geographically distant. The firewalls at both locations complicate matters, necessitating extensive in-person trips by either industrial partners to the university or academic collaborators to the industry. Consequently, during the initial planning of collaboration, it is essential to select a potential third location that is accessible to all parties with minimal complexity, while also ensuring adequate security that is acceptable to both parties.

3. METHODOLOGICAL FRAMEWORK USED IN THIS WORK

The technique is based on a literature analysis of Tertiary institution-Industry Partnerships, sourced from indexed materials, and focused on literature reviews in the domain, together with case-based experiences that provide practical input. This study offers a critical analysis of the essential elements concerning the interaction between higher education institutions and industry. The methodology employed in developing the article comprised two phases: (i) identifying the principal theme of the research via a comprehensive literature review on ScienceDirect, Google Scholar, Springer, Taylor & Francis, and prominent indexed journals in SCOPUS utilising the terms “Collaboration,” “Knowledge Transfer,” “Competitiveness,” and “Value Creation,” and (ii) selecting significant case studies that focus on the central topic and address the relational issues. To guarantee the inclusion of pertinent case studies and reviews on collaboration mechanisms related to the Tertiary Institution-Industry relationship, relevance was prioritised alongside a temporal constraint of the past decade, specifically from 2014 to 2019, with certain exceptions for historical reports, agreements, or governing acts. The most frequently visited articles over the period were examined to verify and classify the themes.

3.1 Collaboration Strategies and Competitive Advantage

The term collaboration connotes favourable notions of interaction and the unification of efforts towards a specific achievement. Individuals that engage in collaboration do so with the anticipation of attaining, through engagement with others, something that they previously lacked. This method can yield professional growth and enhancements in the domains in which they function. Collaboration is thus a mechanism that fosters the advancement of individuals and activities, as well as the organisations to which they are affiliated (Reficco et al., 2018). In a collaborative relationship, responsibility must be equitably distributed and accepted by all stakeholders, irrespective of their distinct roles (Lin, 2017). This process must consider four elements: Conceptual convergence, emphasising the necessity of a mutual understanding of collaboration and the commitment to work together towards a common goal, thereby fostering a shared vision; Agreement on the definition of objectives, which underscores the significance of collective clarity leading to actionable strategies in which all participants can identify and engage; Shared management, which stresses the collective responsibility for overseeing the process; and, finally, the anticipation of individual outcomes that should yield benefits for each participant, their respective organisations, and society, in relation to the undertaken activities and the individuals involved. In collaborative endeavours, the collective desire to achieve shared goals must be paramount, necessitating trust in others, appreciation of their expertise and experience, and the belief that collective progress surpasses individual efforts (Un and Rodríguez, 2018). The production of ideas for problem-solving is the currency of the future and must be tackled by well-integrated teams (Edmondson, 2012). Consequently, versatile and proficient firms that can navigate change and possess the capabilities to accelerate and disrupt the business environment will be more strategically positioned to tackle present and future issues.

Competitive advantage is analysed through two predominant theories: one posits a market-based perspective, asserting that the industry's structure and competitive dynamics are the primary determinants of a company's performance, while the other adopts a resource-based view, highlighting the significance of the resources utilised by companies as the principal source of competitive advantage (Ghadimi, Ghassemi Toosi and Heavey, 2018). The concept of core competences is intricately linked to a resource-based vision, which also encompasses knowledge-based and capability-based perspectives. The relational approach, a recent formulation, has garnered significant attention, positing that in today's globalised economy, most organisations are unable to effectively navigate quickly changing competition relying solely on their own resources and competencies. Contemporary organisations attain success through a sustained competitive advantage, derived from their capacity to cultivate a set of core skills that enable them to better address customer demands than their competitors (Eftimoski & Milenkovski, 2012).

4.0 COMPETITIVENESS VERSUS INNOVATION

Business leaders confront escalating competitiveness, globalisation, technology advancements, and novel strategy paradigms. In a competitive and dynamically changing environment, these elements must be handled to establish and maintain a high-performance organisation. It is essential to consolidate limited resources to attain critical mass, thereby enhancing the introduction of innovation in the market and fostering collaboration, particularly in research and innovation activities that drive productivity development and industrial competitiveness. Innovation has historically been regarded as a survival mechanism due to increasing competition (Smirnova, Rebiazina, and Khomich, 2018), with the impetus for innovation arising from either explicit market needs or from research and development initiatives within organisations. Innovation is not merely a process of generating ideas; it is also the outcome of intricate social interactions, communication, and the exchange of knowledge.

The generation of innovation within a company encompasses two elements: resources and the capacity to establish networks. While innovation is not exclusively a trait of companies engaged in networks, it can also occur in standalone entities (Konsti-Laakso, Pihkala, and Kraus, 2012).

Furthermore, a positive correlation exists between growth, innovation, and the utilisation of diverse external relationships. The advancement of innovation necessitates backing for research and development, as well as collaboration with other organisations (Jørgensen and Ulhøj, 2010). Consequently, the networks offer a viable alternative that allows organisations, especially SMEs, to surmount their limitations and foster innovation. The literature indicates that consumers play an active role as a crucial component in value co-creation during innovation activities (Liao, Hu, and Ding, 2017). This perspective includes novel methods of client engagement (Santos, Murmura, and Bravi, 2019), along with their interaction and incorporation into the company's innovation activities (Cui and Wu, 2016; Ferreira Rebelo, Silva, and Santos, 2017; Araújo et al., 2019). The fundamental aspect of this method pertains to the newly-enabled client and connectivity that utilises recent technological advancements to enhance engagement and oversight of innovations within organisations (Orviská et al., 2019; Barbosa, de Oliveira, and Santos, 2018).

Knowledge is the fundamental element that sustains the competitiveness of regions, nations, industries, and enterprises. The generation of high added value in the global economy relies on innovation, which is predicated on the capacity to conceive and convert novel ideas into

commercially viable products and processes. The health and prosperity of civilisations increasingly rely on their capacity for innovation, with science and technology serving as a crucial source of competitive advantage. Connecting fundamental and applied research to the market via technology transfer and marketing strategies, including collaborations among government, higher education institutions, and industry, as well as capital investment, will serve as the primary catalyst for sustainable competitive advantage and prosperity (Carayannis and Campbell, 2012). The public—comprising media, culture, and civil society—utilizes and implements knowledge, so participating in the innovation system. In a knowledge-based society and advanced economy, knowledge circulates throughout all sectors of society. Diverse and diversified cultural configurations should foster creativity, which is vital for the generation and development of new knowledge and technologies. This fosters the creation of "creative knowledge spaces," which are situations and contexts that positively impact individuals engaged in creative endeavours (Resetarits and Resetarits-Tincul, 2012).

An advanced knowledge economy simultaneously fosters innovation and creativity; as it matures, it necessitates increased creativity, as it can assimilate greater knowledge, innovation, and creativity (Dubina, Carayannis, and Campbell, 2012; Chi et al., 2018). The creative economy intricately connects technology discoveries with social advancements. The competitiveness and superiority of a knowledge system, as well as its advanced developmental stage, are significantly influenced by its capacity to adapt, amalgamate, and integrate diverse forms of knowledge and innovation (Carayannis and Campbell, 2012). A significant fact is that knowledge is socially built and is enhanced through partnerships where participants exchange information and engage in projects that integrate characteristics, real-world content, and diverse sources of information within teams. This is the most broadly endorsed contemporary strategy, particularly with the use of information technology, hence enhancing collaboration and knowledge transfer's prominence.

4.1 Collaboration with higher education institutions

Multinational corporations have established paradigms in forming international networks termed "Centres of Excellence" in collaboration with tertiary and research institutions, which hold strategic significance for public administration at two distinct levels: nationally, it augments the nation's research and knowledge capital; locally, it fosters the engagement of key economic and academic stakeholders, serving as a singular resource to advance sustainable and enduring regional development. The strategic partnership is an organisational structure aimed at integrating various elements of intellectual capital, concentrating on specific initiatives, where each partner contributes operational challenges and distinct corporate cultures. European tertiary schools are thought to enhance their appeal greatly, as collaborations are a clear emphasis and an increasing number of academics have experience in the corporate sector (Edmondson et al., 2012). The European Union has acknowledged the significant importance of higher education institutions in transferring knowledge to society and their crucial contribution to the competitiveness of the European economy through education, research, and innovation (Plewa et al., 2013). However, when higher education institutions collaborate with industry, the potential for synergy is sometimes hindered by communication breakdowns. Despite the facilitation of access to research findings through modern information and communication technologies, a significant disparity persists between the knowledge generated by researchers and its use in practice. The "European paradox" illustrates a robust research capability yet a deficiency in converting this into creative products (Ranga et al., 2013). The reasons for this gap are primarily attributed to researchers who frequently

exhibit greater interest and allocate more time and effort to the generation of new knowledge rather than its dissemination.

Numerous authors contend that the cornerstone of effective knowledge transfer is a continuous dialogue process and the development of social networks; therefore, significant emphasis should be placed on cultivating robust personal relationships, rather than institutional ones, and fostering trust, which is a crucial element in business (Johnston and Huggins, 2016). The partnership between the tertiary institution and the company is founded on a mindset, propelled by intrinsic and psychological factors (trust, mutual commitment, shared objectives) rather than by regulations or measurable components (Edmondson et al., 2012). The literature indicates that facilitators influencing the establishment and sustenance of Industry-Tertiary institution collaborations include confidence (Schilke and Cook, 2013) and the presence of collaboration champions, recognising their effect on technology and educational outcomes. While collaboration among organisations can be facilitated through many ways, the significance of trust in establishing and sustaining the connection should be emphasised (Huang and Wilkinson, 2014). Trust is an essential component of effective negotiations; when negotiators trust one another, they are more inclined to formulate strategies for value creation and problem-solving, which includes information sharing, addressing needs, and assisting the other party in achieving its objectives (de Klerk, 2012). Within inter-cooperative systems, trust constitutes mutual confidence; no agent should abuse the vulnerabilities of others. Consequently, it is linked to the specific danger of the "problem" and serves as a solution for its resolution. Trust is devoid of significance in the absence of an environment characterised by uncertainty or risk. Trusting entails navigating the peril of wagering on an unpredictable future (Nguyen and Liem, 2013). Trust is established through inter-organizational interactions over time and increasingly influences the maintenance of these ties (Schilke and Cook, 2013). In conclusion, trust arises from behaviour deemed "right," "fair," and "serious," where decisions and morally sound actions are grounded in ethical principles that acknowledge and safeguard the rights and interests of others (Hewitt-Dundas, Gkypali, and Roper, 2019).

A good partnership requires meticulous planning and cultivation; thus, it is essential to comprehend the factors that contribute to its success (Rajalo and Vadi, 2017). When new knowledge emerges from a collaborative project, the viewpoints of the involved parties frequently shift (Bruneel, D'Este and Salter, 2010). Scholars are motivated to disseminate findings early to enhance their standing within the scientific community, whereas companies tend to delay disclosure to maintain a competitive edge. Additional possible conflicts may emerge from divergent perspectives on intellectual property rights or variances in language and values that influence communication (Hewitt-Dundas, Gkypali and Roper, 2019). It is essential that the intentions and goals of each partner are distinctly articulated and elucidated. Furthermore, it is essential that all partners possess the ability to impact decisions that effect the relationship (Anderson, Michael and Peirce, 2012). Eliminating obstacles alone is insufficient; the catalysts for partnership and the existence of clear advantages, which serve as incentives, are essential for fostering collaboration (Edmondson et al., 2012), thereby cultivating trust among all stakeholders (Piacentini, 2013; Rehák, Šipikal, and Lešková, 2019).

4.2 Principal Constraints in Collaborative Strategies

The report highlights essential factors that educational institutions and corporations must consider when forming partnerships to achieve a competitive edge through collaboration and facilitate future cooperative endeavours. The following guidelines encapsulate results related to the sustainable growth of a tertiary institution-enterprise cooperation. Table 1 summarises key characteristics frequently overlooked by partnerships, as validated by several authors, which typically result in unsatisfactory collaborations. The following issues are examined and studied from a constructive standpoint, emphasising the benefits and contributions to healthier and more productive partnerships.

Table 1 – Overlooked Collaborative Elements in Partnerships

Collaboration	Source
Partner Selection	Giesecke (2012), Ranga and Etzkowitz (2013), Bunduchi (2013), Thune and Gulbrandsen (2014), Le Roy, Robert and Lasch (2016), Mindruta, Moeen and Agarwal (2016), Johnston and Huggins (2016), Criscuolo et al. (2017), Yoon et al. (2017), Ankrah and Al-Tabbaa (2017), Hartman and Dhanda (2018), Frølund, Murray and Riedel (2018), Reichert (2019)
Collaboration Management	Giesecke (2012), Ranga and Etzkowitz (2013), Ankrah and Omar (2015), Sum Chau, Mark and Serbanica (2016), Grimpe, Goel and Göktepe-Hultén (2017), Jonkers et al. (2018), Hartman and Dhanda (2018), Merritt and Kelley (2018), Frølund, Murray and Riedel (2018), Reichert (2019)
Interface Management	Giesecke (2012), Ranga and Etzkowitz (2013), Plewa et al. (2013), Thune and Gulbrandsen (2014), Perkmann and Schildt (2015), Yoon et al. (2017), Ankrah and Al-Tabbaa (2017), Champenois and Etzkowitz (2018), Al-Tabbaa and Ankrah (2018), Reichert (2019)
The Use of Champions	Ranga and Etzkowitz (2013), Plewa et al. (2013), Bstieler, Hemmert and Barczak (2015), Sum Chau, Gilman and Serbanica (2016), Yoon et al. (2017), Veles, Carter and Boon (2018), Merritt and Kelley (2018), De Silva, Howells and Meyer (2018), Reichert (2019)
Long-term partnership	Perkmann and Salter (2012), Giesecke (2012), Ranga and Etzkowitz (2013), Thune and Gulbrandsen (2014), Yoon et al. (2017), Frølund, Murray and Riedel (2018), Reichert (2019)
Shared Vision and Strategy	Giesecke (2012), Ranga and Etzkowitz (2013), Thune and Gulbrandsen (2014), Bstieler, Hemmert and Barczak (2015), Sum Chau, Gilman and Serbanica (2016), Yoon et al. (2017), Ankrah and Al-Tabbaa (2017), Hartman and Dhanda (2018), Frølund, Murray and Riedel (2018), de Wit- de Vries et al. (2018), Reichert (2019)

The literature identifies two distinct phases in the evolution of the collaborative process: "partner selection" and "partnership management," which are crucial for its overall effectiveness. In selecting a partner, it is essential to align the goals of the corporations with the capabilities of the tertiary school to ensure the success of the cooperation. Collaboration history, geographical proximity, and technological skills are significant aspects to consider. In the second phase, the management of the partnership becomes significant, as the outsourcing of innovation is susceptible to opportunism from both parties, due to the constraints of unpredictability and oversight. Academics and corporations pursue collaborators with aligned goals and competencies, whose assessment is contingent upon the project's success. Therefore, a crucial connection must be established to guarantee frequent and continuous personal engagement between researchers from

academic institutions and industry managers. Collaborations are effective only when overseen by those who navigate boundaries effortlessly and possess profound knowledge of both cultures, therefore necessitating the involvement of Champions.

The initial step towards a robust partnership involves identifying the primary strengths of the tertiary institution and the core competences of the enterprise, with the objective of uncovering potential collaboration prospects. A comprehensive grasp of the three distinct sorts of potential partnerships—strategic, operational, or transactional—is necessary to identify the one that most appropriately aligns with both parties. Clearly stated, achievable, and mutually agreed-upon objectives are crucial components in the administration of collaborative projects. In the absence of clearly delineated objectives, initiatives often expand excessively and exceed their original parameters. Furthermore, the significance of the project leader and proficient communication must be underscored to consistently align objectives with expectations. There is no expedient method to develop personal relationships that may result in more innovative and advantageous cooperation. Tertiary institutions ought to facilitate chances for scholars, researchers, and executives from related industries to convene and engage in discourse. The most productive collaborations require time to yield outcomes.

5. CONCLUSION

Numerous studies underscore the pivotal significance of higher institutions as facilitators of substantial chances for knowledge creation, alongside their educational and research functions, hence transforming their position in marketing and greatly enhancing innovation. Research findings indicate that firms generally do not leverage links with higher institutions to enhance and develop key competences due to the persistent cultural and philosophical disparities between industry and academia. Tertiary institutions possess a distinct temporal focus and objectives compared to industrial enterprises. Moreover, literature indicates that companies are wary of relying on tertiary institutions, particularly in domains vital for establishing competitive advantage, despite evidence suggesting that this is an overlooked area with significant potential benefits for organisations. Consequently, challenges persist regarding trust and comprehension of operations on both sides. Minimising complexity, cultivating relationships, and implementing effective intermediation, especially for small enterprises, are recommendations that uphold robust, trustworthy connections between individuals in industry and academia, establishing the groundwork for successful collaboration. Partnerships frequently neglect to adequately define the anticipated outcomes for both parties, resulting in the degradation of the relationship. The assembled list of critical overlooked components underscores the imperative for prioritising elements such as: Partner Selection; Collaboration Management; Interface Management; Utilisation of Champions; Long-term Partnerships; and Shared Vision and Strategy. Individuals are essential for ensuring the efficacy and sustainability of any partnership, which is frequently compromised by inadequate leadership and disregard for stakeholders' interests. Long-term alliances cultivate the human capital essential for the functioning of industry-tertiary institution collaborations. Over time, a well-managed partnership yields an increasing number of educators and graduate students capable of navigating cultural divisions, aligning with the company's primary research interests, and collaboratively establishing overarching common objectives. Both companies and academia must establish regulations to mitigate the detrimental consequences of overlooked crucial relationship elements.

Numerous authors have articulated the substantial advantages of forming a collaboration between academia and industry. This report delineated some obstacles and issues associated with these relationships. The primary aim of this study is not to assert that developing these relationships is worthless of effort, but rather to indicate that there are some problems associated with them. Prior to attempting to establish such a collaboration, one must first recognise these problems and formulate solutions to handle them. Amid the stringent financial constraints faced by most institutions, professors and university administrators may be inclined to seize financing opportunities arising from such collaborations. Failure to adequately address these problems may render the money a liability rather than a remedy for departmental requirements. It is evident that many issues outlined in this study are beyond the collaborators' control, while solutions to other challenges are contingent upon the policies of the particular collaborating institutions. Our experience indicates that solutions tailored to a particular collaborating partner may not be applicable to another, rendering it very hard to devise a universal solution for any of the challenges addressed in this study that might be utilised by others. This paper aims to inform others about potential challenges encountered in collaborative partnerships with industry and to highlight issues requiring attention during risk analysis prior to establishing such partnerships.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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SOCIOECONOMIC CHALLENGES FOR RENEWABLE ENERGY DEPLOYMENT AND PROSPECTS FOR TRANSITION TO RENEWABLE ENERGY

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Abstract

The global shift to renewable energy is a complex undertaking that requires significant socioeconomic changes. This study sought to examine the socioeconomic problems and opportunities associated with this transformation. This research offers insights into the economic, social, technological, and policy aspects of renewable energy adoption by a thorough examination of existing literature and case studies. The research utilised a mixed-methods approach, integrating qualitative analysis of policy frameworks with quantitative evaluation of economic effects. Principal findings reveal that although renewable energy technologies, including solar and wind, are becoming more cost-competitive, substantial initial capital expenditures and extended payback durations continue to pose considerable obstacles. Social and cultural opposition presents obstacles, especially in areas with deep connections to conventional energy sources. Inconsistencies in policy and uncertainty in regulation exacerbate the challenges associated with the deployment of renewable energy technologies. In contrast, the report underscores several potentials. The implementation of renewable energy can significantly generate employment, invigorate local economies, and improve energy enhancing security through the diversification of energy sources. Advancements in energy storage and smart grids are essential for the integration of renewable energy into current systems, maintaining reliability and stability. Robust policy frameworks, like feed-in tariffs and carbon pricing, are crucial for promoting investment and innovation in the renewable energy industry. The study indicates that a comprehensive approach, incorporating economic incentives, social involvement, and strong

governmental frameworks, is essential for addressing difficulties and optimising the advantages of renewable energy. Future research should focus on investigating novel financial structures, improving energy storage technologies, and augmenting public participation to foster social acceptance of renewable energy initiatives.

1.0 INTRODUCTION

The worldwide shift to renewable energy represents not just a technological change but also a significant societal transformation. This transition entails substituting fossil fuels with renewable energy sources, including solar, wind, hydro, and biomass, which has significant ramifications for economies, society, and the environment. As countries endeavour to achieve climate objectives and diminish greenhouse gas emissions, comprehending the socioeconomic obstacles and prospects of this transition is essential. The adoption of renewable energy is essential for minimising climate change, decreasing reliance on fossil fuels, and fostering sustainable development (IPCC, 2018). The transformation is, however, laden with socioeconomic problems that differ among areas and communities. These issues encompass elevated initial capital expenditures, technological ambiguities, and the necessity for significant infrastructure investments (Sovacool, et al., 2014). Moreover, societal acceptance and cultural obstacles can hinder the use of renewable technologies (Sovacool, 2009).

Economic obstacles provide substantial impediments to the transition to renewable energy. Significant initial expenditures and extended payback durations dissuade investors and governments from engaging in large-scale renewable initiatives (Sovacool, et al., 2014). Additionally, funding renewable energy initiatives continues to be problematic due to perceived risks and uncertainties linked to emerging technology (Bazilian et al., 2011). Economic hurdles are especially evident in poorer nations, when capital availability is constrained and financial systems are underdeveloped.

Social and cultural obstacles significantly influence the transition to renewable energy. The public's view and acceptability of renewable energy technology differ significantly across areas (Sovacool, 2009). In certain areas, resistance to change arises from a deficiency of awareness or comprehension of the advantages of renewable energy. Cultural values and conventions can also affect the uptake of renewable technologies. Communities having a deep affinity to conventional energy sources may exhibit resistance to adopting new technology (Sovacool, 2009).

The significance of policy and governance in enabling the renewable energy transition is paramount. Robust legislative frameworks and conducive regulatory regimes are crucial for attracting investments and promoting the uptake of renewable technologies (Smith, et al., 2005). Nonetheless, uneven rules and regulatory ambiguities might impede advancement. Governments must deliver unequivocal and consistent policy signals to cultivate investor confidence and secure long-term commitments to renewable energy (Smith, et al., 2005). Notwithstanding these hurdles, the switch to renewable energy offers several prospects for socioeconomic advancement. A vital opportunity is the generation of employment. The renewable energy business is labour-intensive and possesses the capacity to create millions of jobs worldwide (IRENA, 2018). This is especially significant in areas with elevated unemployment rates and can facilitate economic expansion and poverty reduction.

Furthermore, renewable energy can bolster energy security by diversifying the energy supply and diminishing reliance on imported fossil fuels (REN21, 2019). This diversification can safeguard economies from fluctuating fossil fuel prices and bolster resilience against energy supply interruptions. Moreover, renewable energy initiatives can invigorate local economies by creating new business prospects and promoting innovation (REN21, 2019).

The ecological advantages of renewable energy are well recorded. Renewable energy can alleviate climate change and enhance air quality by decreasing greenhouse gas emissions, resulting in improved public health outcomes (Ellis and Ferraro, 2016). Moreover, renewable energy initiatives might provide beneficial social effects by enhancing electricity accessibility in isolated and underprivileged regions. This can improve life quality and facilitate sustainable development objectives (Bazilian et al., 2011).

Technological developments and innovations are essential catalysts for the transition to renewable energy. Ongoing advancements in technology have resulted in substantial cost reductions and enhanced efficiency of renewable energy systems (Bazilian et al., 2011). The price of solar photovoltaic (PV) modules has significantly declined over the last decade, enhancing the competitiveness of solar energy against conventional energy sources (Bazilian et al., 2011). Moreover, advancements in energy storage and smart grid technology are improving the incorporation of renewable energy into current energy systems (Bazilian et al., 2011, Naiho et al., 2024b).

The transition to renewable energy requires a reevaluation of energy governance. Conventional energy systems are centralised and hierarchical, while renewable energy systems are decentralised and participative (Smith et al., 2005). This transition necessitates novel governance frameworks that promote stakeholder involvement and guarantee equitable distribution of renewable energy gains (Smith, et al., 2005). Inclusive governance frameworks can improve societal acceptability and endorsement of renewable energy initiatives (Smith, et al., 2005).

As the shift to renewable energy advances, it is crucial to confront the vulnerabilities and disparities that may emerge. Vulnerability analysis frameworks can identify the most susceptible people and guarantee they are not disproportionately impacted by the transition (Turner et al., 2003). This is especially significant in developing nations, where the socioeconomic effects of the shift may be more evident (Turner et al., 2003). Facilitating an inclusive and equitable transition is essential for realising the overarching objectives of sustainable development and social fairness (Turner et al., 2003).

In conclusion, the move to renewable energy poses considerable problems and potential from a socioeconomic standpoint. Confronting these difficulties necessitates a holistic strategy encompassing economic incentives, social involvement, and robust policy frameworks. Simultaneously, capitalising on the potential linked to renewable energy can stimulate economic expansion, bolster energy security, and advance environmental sustainability. This study aims to investigate the socioeconomic problems and opportunities in the renewable energy transition, emphasising the identification of solutions to surmount obstacles and optimise advantages. The aim is to deliver an exhaustive study of the present status of the renewable energy transition and

to propose insights for future research trajectories. The study encompasses an analysis of economic, social, and policy factors, including case studies and exemplary practices globally.

2. THE SOCIOECONOMIC FRAMEWORK OF RENEWABLE ENERGY

The shift to renewable energy is transforming the global socioeconomic landscape, with considerable effects on economic growth, social fairness, and environmental sustainability. Renewable energy sources, including wind, solar, and hydropower, are progressively incorporated into the energy mix, motivated by the necessity to alleviate climate change and diminish reliance on fossil fuels (Bhattacharya et al., 2016). This transformation is creating new economic opportunities but also introducing issues that must be addressed to guarantee an equitable shift.

Economic expansion is a primary catalyst for the uptake of renewable energy. Research indicates that the consumption of renewable energy fosters economic growth, especially in nations endowed with substantial renewable resources (Bhattacharya et al., 2016). The implementation of renewable energy initiatives generates employment, invigorates local economies, and draws investments. The establishment and upkeep of renewable energy infrastructure necessitate a proficient personnel, thereby creating employment chances in several sectors (IRENA, 2019). The renewable energy sector is garnering significant financial investments, essential for the expansion of renewable energy projects and technologies (Mazzucato and Semieniuk, 2018).

The shift to renewable energy prompts significant enquiries for social equity and justice. The allocation of benefits and expenses associated with renewable energy projects is inequitable, frequently intensifying pre-existing societal disparities (Carley and Konisky, 2020). Communities hosting renewable energy initiatives may have both beneficial and detrimental effects. They can gain from enhanced local infrastructure, job generation, and community investments. Conversely, they may encounter disturbances to their lifestyle, land use conflicts, and environmental issues (Enevoldsen et al., 2019). Achieving a just and equitable transition necessitates inclusive decision-making procedures that include the interests and perspectives of all stakeholders, including marginalised populations (Carley and Konisky, 2020).

The problem of fossil fuel subsidies constitutes another considerable challenge. Notwithstanding international pledges to diminish carbon emissions, fossil fuel subsidies persist significantly, distorting the energy market and impeding the competitiveness of renewable energy (Coady et al., 2017). These subsidies, totalling hundreds of billions of dollars each year, promote the ongoing utilisation of fossil fuels and hinder the shift to greener energy alternatives. Eliminating fossil fuel subsidies and reallocating financial assistance to renewable energy can expedite the transition and foster a more sustainable energy system (Coady et al., 2017). Climate change and energy security are intricately connected to the shift to renewable energy. Renewable energy sources can bolster energy security by diversifying the energy supply and diminishing dependence on imported fossil fuels (Sovacool et al., 2020). This is especially pertinent to nations in the Asia-Pacific area, which exhibit a significant reliance on energy imports and are susceptible to supply interruptions. By augmenting the proportion of renewables in their energy portfolio, these nations can enhance their energy security and resilience to external disruptions (Sovacool et al., 2020). The social cost of carbon is a significant factor in the shift to renewable energy. This statistic, which quantifies the economic costs linked to carbon emissions, highlights the imperative of shifting to low-carbon energy sources (Jones and Summers, 2020). Incorporating the social cost of carbon into energy

policy and investment decisions enables governments and corporations to more effectively consider the environmental and social repercussions of their activities. This strategy can promote the utilisation of renewable energy and advance the overarching objectives of climate change mitigation and sustainable development (Jones and Summers, 2020).

Gender perspectives are essential for comprehending the socioeconomic framework of renewable energy. Women frequently assume a crucial role in the energy sector, especially in rural and marginalised populations (IRENA, 2019). Empowering women with renewable energy programs may augment their livelihoods, expand energy accessibility, and foster gender equality. Gender-sensitive policies and programs are crucial to guarantee equitable distribution of the advantages of the renewable energy transition and to enable women's active participation in decision-making processes (IRENA, 2019).

The transition to renewable energy is reshaping the socioeconomic environment, presenting both opportunities and problems. The transition encompasses essential characteristics such as economic growth, social fairness, energy security, and environmental sustainability. Confronting socioeconomic issues and capitalising on opportunities necessitates a comprehensive approach that amalgamates economic, social, and environmental factors. This strategy will guarantee an equitable and sustainable shift to renewable energy, advantageous for both present and future generations.

2.1 Challenges in the Transition to Renewable Energy

The shift to renewable energy is essential for sustainable development; nonetheless, it has various problems that must be resolved to attain widespread implementation. These problems include economic, social, cultural, and policy-related obstacles that can hinder the advancement of renewable energy initiatives. A significant economic barrier is the substantial initial capital expenditure required for renewable energy plants. In contrast to fossil fuel initiatives, which leverage existing infrastructure and economies of scale, renewable energy projects typically necessitate substantial upfront expenditures in technology, infrastructure, and development (Sovacool, et al., 2014). The elevated expenses may dissuade investors and restrict financing options, especially in poor nations where financial resources are limited (Mazzucato and Semieniuk, 2018). Additionally, renewable energy initiatives are regarded as bearing elevated financial risks due to the fluctuations in energy production and extended payback durations, which further complicate investment choices (Mazzucato and Semieniuk, 2018).

Social and cultural obstacles present considerable difficulties to the shift to renewable energy. Public perception and acceptance of renewable energy technology differ significantly, with resistance to change sometimes stemming from a lack of awareness or disinformation (Sovacool, 2009). Cultural values and conventions can affect perceptions of renewable energy, with certain populations exhibiting a pronounced inclination towards conventional energy sources (Sovacool, 2009). This opposition may be intensified by apprehensions regarding the environmental and social ramifications of renewable energy initiatives, including alterations in land usage, visual disturbances, and noise pollution (Enevoldsen, et al., 2019). Surmounting these obstacles necessitates extensive public engagement techniques encompassing education, transparency, and the participation of local communities in decision-making processes (Enevoldsen, et al., 2019).

Policy and regulatory obstacles are also substantial. Inconsistent and unstable policy frameworks generate uncertainty for investors and project developers, obstructing the advancement of renewable energy (Coady et al., 2017). Robust legislative measures are essential to establish unequivocal incentives and sustained commitments to renewable energy. The existence of fossil fuel subsidies persists in distorting energy markets, hindering renewable energy's ability to compete equitably (Coady et al., 2017). Discontinuing these subsidies and reallocating financial assistance to renewable energy will foster a more equitable energy market and expedite the transition.

A significant difficulty is the quantification and integration of the social cost of carbon into energy policies and investment strategies. The social cost of carbon quantifies the economic damages linked to an extra tonne of carbon dioxide emissions, underscoring the necessity of emission reduction via the implementation of renewable energy (Jones and Summers, 2020). Integrating this cost into energy planning necessitates rigorous methodology and international collaboration to guarantee that all externalities are precisely accounted for and incorporated into energy prices (Jones and Summers, 2020).

In conclusion, tackling the obstacles in the renewable energy transition necessitates a multifaceted strategy encompassing financial innovation, public involvement, legislative reforms, and international collaboration. By surmounting these obstacles, the global community may achieve substantial progress towards a sustainable and resilient energy future.

2.2 Prospects in the Transition to Renewable Energy

The global transition to renewable energy offers numerous prospects that surpass environmental advantages, including economic development, social fairness, and energy security. As nations progressively embrace renewable energy technology, they create new avenues for sustainable growth and economic resiliency. The renewable energy transition presents a substantial opportunity for job growth. The renewable energy business is far more labour-intensive than traditional fossil fuel industries, offering extensive employment opportunities throughout several stages of the supply chain, such as manufacture, installation, maintenance, and operations (IRENA, 2018). The International Renewable Energy Agency (IRENA) said that the renewable energy sector employed 11 million individuals worldwide in 2018, with projections indicating growth as investments in green energy increase (IRENA, 2018). These positions not only offer direct employment but also invigorate local economies by generating demand for ancillary services and industries.

The move to renewable energy presents a significant opportunity for economic growth. Investments in renewable energy infrastructure can serve as a spur for economic development, especially in areas currently without access to conventional energy sources. Renewable energy initiatives can garner substantial capital commitments from both governmental and private sectors. Promoting innovation and technical progress (REN21, 2019). Moreover, as renewable energy technologies attain greater cost competitiveness, they present a feasible substitute for fossil fuels, hence decreasing energy expenses for both consumers and enterprises (REN21, 2019).

Energy security is an essential component of the shift to renewable energy. Diversifying the energy

supply through renewable sources mitigates reliance on imported fossil fuels, so bolstering national energy security and resilience to geopolitical threats and market volatility (Sovacool et al., 2020). Countries in the Asia-Pacific area, heavily dependent on energy imports, can markedly enhance their energy security by augmenting the proportion of renewables in their energy mix (Sovacool et al., 2020). This diversification mitigates susceptibility to supply shocks and stabilises energy prices, hence enhancing economic stability.

The switch to renewable energy provides significant environmental advantages, resulting in long-term economic savings. Renewable energy diminishes greenhouse gas emissions, hence alleviating the effects of climate change and resulting in decreased healthcare expenditures due to air pollution and climate-induced health problems (IEA, 2020). Moreover, the transition to clean energy helps mitigate the expenses associated with environmental degradation and biodiversity loss, which are frequently overlooked in conventional economic models (Ekins, McGlade and Bradshaw, 2015). These ecological advantages bolster the overarching objectives of sustainable development and improve the quality of life for global societies.

A further opportunity exists in the potential for an environmentally sustainable recovery following economic recessions. Investing in renewable energy can be a crucial component of economic recovery measures, offering a green stimulus that enhances economic activity while aligning with climate objectives (Barbier, 2010). Green recovery plans can promote sustainable development by emphasising investments in renewable energy infrastructure, energy efficiency, and low-carbon technologies, thus fostering a more robust and sustainable economy (Barbier, 2010). Technological innovations in renewable energy also offer substantial opportunities. Ongoing advancements in technology have resulted in significant cost reductions and enhanced efficiency of renewable energy sources. Advancements in solar photovoltaic (PV) technology have markedly reduced the cost of solar energy, enhancing its accessibility and competitiveness with fossil fuels (Jacobson et al., 2018). Advancements in energy storage and grid management are improving the stability and integration of renewable energy, mitigating the intermittency challenges linked to certain renewable sources (Jacobson et al., 2018).

In conclusion, the move to renewable energy has numerous prospects that surpass mere environmental sustainability. It guarantees economic expansion, employment generation, energy independence, and substantial technological progress. By capitalising on these opportunities, communities may establish a more resilient and sustainable future, guaranteeing that the advantages of the energy transition are broadly disseminated and contribute to global development objectives.

2.3 Case Analyses and Exemplary Practices

The shift to renewable energy is characterised by varied experiences across distinct areas and settings. Analysing case studies and exemplary practices yields significant insights into effective methods and the obstacles faced during implementation. This section emphasises significant instances from many global regions, illustrating the potential and intricacies of renewable energy implementation. The development of wind power in China exemplifies rapid growth propelled by favourable policies and institutional structures. The Chinese government enacted a set of regulations comprising feed-in tariffs, obligatory grid connections, and significant public investments in wind energy infrastructure (Zhang, et al., 2013). These steps enabled the nation to

become the global leader in installed wind capacity. The efficacy of China's wind power strategy underscores the significance of robust governmental backing and extensive policy frameworks in the expansion of renewable energy initiatives (Zhang, et al., 2013).

The photovoltaic (PV) sector in Germany exemplifies successful integration of renewable energy. The Renewable Energy Sources Act (EEG) in Germany established set feed-in prices for solar energy, guaranteeing long-term financial security for investors (Wirth, 2018). This legislation, along with public endorsement and technology progress, positioned Germany as a leader in solar PV adoption. The nation's dedication to solar energy has not only diminished greenhouse gas emissions but also fostered technological innovation and established a strong domestic market for photovoltaic technologies (Wirth, 2018).

Community energy initiatives in Europe, especially wind power cooperatives, exemplify the significance of local involvement and ownership in renewable energy endeavours. Denmark and Germany have had notable success with community-owned wind farms, wherein local inhabitants invest in and get benefits from the projects (Bauwens, et al., 2016). This concept promotes social acceptance, guarantees that economic advantages remain within the community, and stimulates popular endorsement for renewable energy (Bauwens, et al., 2016). The European experience highlights the capacity of community energy to facilitate decentralised renewable energy implementation.

In developing nations, utilising local capacity for solar PV installation has demonstrated encouraging outcomes. IRENA's report on the advantages of renewable energy emphasises the successful implementation of solar home systems in countries such as Bangladesh and Kenya, which have provided electricity to off-grid rural regions (IRENA, 2020). These projects not only improve energy accessibility but also generate local employment and invigorate the economy. Educating local technicians and engaging community organisations have been essential for the durability and scalability of these initiatives (IRENA, 2020).

The Solar City initiative in South Korea shows the amalgamation of commercial, financial, and policy elements to further urban renewable energy growth. The initiative encompassed six municipalities implementing extensive strategies to enhance solar photovoltaic installations on public edifices and residential zones (Byrne et al., 2017). South Korea exemplified a comprehensive strategy for promoting urban renewable energy adoption by synchronising financial incentives, regulatory assistance, and public involvement. This scenario underscores the necessity of synchronised initiatives across many governance tiers to attain substantial renewable energy integration in urban environments (Byrne et al., 2017).

The deployment of smart grid technology in India offers insights for surmounting technological and infrastructural obstacles. India's ambitious Smart system Mission seeks to modernise the power system through the integration of innovative technologies and renewable energy sources (Luthra et al., 2015). Despite obstacles like elevated expenses and technical intricacies, the effort emphasised the essential function of smart grids in improving efficiency and Dependability of renewable energy systems. The Indian case study underscores the necessity of strategic planning, stakeholder collaboration, and ongoing innovation in tackling infrastructural difficulties (Luthra et al., 2015).

The significance of deployment in technological innovation is illustrated by the lifecycle of many renewable energy sources. Studies demonstrate that extensive implementation of technologies like wind and solar photovoltaic systems enhances technological advancements and decreases costs via learning-by-doing (Huenteler et al., 2016). The feedback loop between deployment and innovation is crucial for enhancing the competitiveness and accessibility of renewable energy technology. The phenomenon of technology life-cycles highlights the necessity of continuous investments and favourable policies to propel technological progress in the renewable energy domain (Huenteler et al., 2016).

In conclusion, these case studies illustrate the complex dimensions of the renewable energy transition, emphasising the importance of policy support, community involvement, technological advancement, and strategic planning. Optimal practices from various places offer significant insights for addressing problems and enhancing the advantages of renewable energy implementation.

3. THE PLACE OF TECHNOLOGY AND INNOVATION IN ENERGY TRANSITION

Technology and innovation are pivotal in the renewable energy transition, facilitating breakthroughs that enhance the efficiency, affordability, and scalability of renewable sources. The ongoing advancement and implementation of renewable energy technologies are crucial for sustainably fulfilling global energy requirements and alleviating the effects of climate change. A pivotal technological advancement in the renewable energy sector is the development and optimisation of wind, solar, and hydroelectric power. These technologies have experienced significant enhancements in efficiency and cost reduction, rendering them progressively competitive with conventional fossil fuels (Jacobson et al., 2018). Advancements in photovoltaic (PV) technology have significantly reduced the cost of solar panels, thereby improving their accessibility and facilitating widespread adoption (Jacobson et al., 2018). Likewise, wind turbine designs have improved in efficiency, harnessing greater energy even under low-wind circumstances (Banos et al., 2011).

Optimisation techniques, encompassing sophisticated algorithms and machine learning methodologies, are utilised in renewable energy systems to enhance their efficiency and integration within the energy grid (Banos et al., 2011; Seyi-Lande et al., 2024). These methods facilitate the optimisation of wind turbine and solar panel placement, forecast energy output, and oversee energy storage and distribution. Utilising big data and artificial intelligence enhances the operational efficiency of renewable energy systems, minimising waste and augmenting reliability (Banos et al., 2011).

Energy storage technologies represent a vital domain of innovation that facilitates the transition to renewable energy. The sporadic characteristics of renewable energy sources such as wind and solar require efficient storage systems to provide a consistent and dependable energy supply (Victoria et al., 2016). Progress in battery technology, particularly lithium-ion and novel solid-state batteries, has markedly enhanced the capacity and efficiency of energy storage systems (Victoria et al., 2016). These storage systems facilitate the acquisition and retention of surplus energy.

During peak production phases, resources can be allocated for use during periods of low

production, thus equilibrating supply and demand (Victoria et al., 2016). The incorporation of smart grid technologies is revolutionising the renewable energy sector. Smart grids employ digital communication technology to oversee and regulate the distribution of electricity from diverse generation sources to satisfy the fluctuating demands of end users (Gielen et al., 2019, Naiho et al., 2024a). These grids augment the efficiency, reliability, and sustainability of electricity supply by facilitating superior integration of renewable energy sources, real-time energy management, and enhanced outage responses (Gielen et al., 2019).

Policy and market mechanism innovation is equally crucial to facilitate technological progress in renewable energy. Incentive mechanisms including feed-in tariffs, renewable energy certificates, and carbon pricing promote the adoption of renewable technology and stimulate investments in research and development (Gielen et al., 2019). These strategies facilitate the surmounting of economic obstacles and expedite the implementation of renewable energy systems (Layode et al., 2024b; Gielen et al., 2019).

Moreover, the significance of international collaboration and knowledge dissemination is paramount. International collaborations and joint research endeavours promote the dissemination of optimal practices and technological advancements across nations (IRENA, 2019). Entities such as the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA) are instrumental in fostering global collaboration and offering venues for collaborative research and development initiatives (IRENA, 2019).

In the area of decarbonisation, technological innovation is propelling the advancement of sector-coupled energy systems. These systems amalgamate various energy sectors, including electricity, heating, and transportation, to enhance overall energy efficiency and diminish carbon emissions (Victoria et al., 2016). Excess renewable electricity can be utilised to generate green hydrogen via electrolysis, which subsequently serves as a clean fuel for many uses, including transportation and industrial activities (Victoria et al., 2016, Layode et al., 2024a).

Ultimately, historical data and future forecasts highlight the transformative capacity of technological innovation within the renewable energy sector (Ahmad and Zhang, 2020). Examining past energy consumption patterns and technical trends yields critical insights into the trajectory of renewable energy adoption and underscores the necessity of ongoing innovation to sustainably address future energy requirements (Ahmad and Zhang, 2020).

In conclusion, technology and innovation are central to the renewable energy transition, propelling advancements that enhance the viability and scalability of renewable energy sources. Ongoing investment in research and development, along with favourable policies and international cooperation, is crucial to fully exploit technological innovations and attain a sustainable energy future.

4. POLICY AND GOVERNANCE FOR SOCIOECONOMIC VIABILITY

The shift to renewable energy constitutes not merely a technological and economic undertaking but also a multifaceted governance challenge. Robust policy frameworks and governance structures are crucial for promoting socioeconomic sustainability during this transition. This

segment examines the place of policy and governance in facilitating sustainable energy transitions and ensuring equitable distribution of gains throughout society.

The governance of sustainable socio-technical transformations necessitates the collaboration of diverse stakeholders, including governmental bodies, business sector organisations, and civil society (Smith et al., 2005). Effective transitions necessitate cohesive policy strategies that encompass economic, social, and environmental aspects. Germany's Energiewende demonstrates a comprehensive policy framework that blends renewable energy deployment with objectives of reducing greenhouse gas emissions and enhancing energy efficiency (Renn and Marshall, 2016). This policy has been bolstered by various instruments, such as feed-in tariffs, subsidies for renewable energy initiatives, and investments in grid infrastructure (Renn and Marshall, 2016). Global energy policies, particularly those promoted by the International Energy Agency (IEA), underscore the necessity of establishing stable and predictable regulatory frameworks to entice investment in renewable energy (IEA, 2020). Policies that offer long-term certainty, including renewable energy targets, tax incentives, and carbon pricing mechanisms, can substantially bolster investor confidence and promote the expansion of the renewable energy sector (IEA, 2020). Political power dynamics significantly influence the formulation of renewable energy legislation. The shift to renewable energy frequently encounters opposition from entrenched fossil fuel industries and their political supporters (Burke and Stephens, 2018). This resistance may manifest in several ways, including lobbying against renewable energy incentives, disseminating misinformation regarding the reliability of renewable technologies, and swaying policy decisions to favour fossil fuels (Geels, 2014). Confronting these power dynamics necessitates robust political commitment and the mobilisation of social backing for renewable energy initiatives (Geels, 2014). Employment and job development are essential components of socioeconomic sustainability during the shift to renewable energy. The renewable energy sector possesses the capacity to generate millions of jobs globally, fostering economic growth and social stability (IRENA, 2020). Policies that promote workforce development, including training programs and educational efforts, are crucial for cultivating the skilled labour force required for the renewable energy sector (IRENA, 2020). Moreover, guaranteeing just labour practices and equitable job allocation can alleviate the social repercussions of the energy transition.

Green growth strategies prioritise the simultaneous objectives of economic expansion and environmental sustainability. Policies that advocate for green growth aim to dissociate economic advancement from environmental deterioration by encouraging innovation and bolstering the eco-industry (Jänicke, 2012). Investments in renewable energy technologies, energy efficiency initiatives, and sustainable transportation can stimulate economic growth while decreasing carbon emissions and preserving natural resources (Jänicke, 2012). Green growth policies promote the establishment of new markets and industries, fostering opportunities for economic diversification and resilience.

Policy coherence and integration are essential for the efficacy of renewable energy governance. Disjointed policies may result in inefficiencies and contradictory aims, compromising the overarching objectives of the energy transition (Smith et al., 2005). Integrating energy policies with Comprehensive economic, social, and environmental policies can improve policy coherence and optimise the advantages of the energy transition (Smith, et al., 2005). This necessitates

intersectoral cooperation and the synchronisation of policy goals at local, national, and international tiers.

Public participation and stakeholder engagement are vital elements of effective governance in renewable energy transitions. Inclusive decision-making processes that engage diverse stakeholders, such as local communities, industry representatives, and environmental organisations, can augment the legitimacy and acceptance of renewable energy policies (Burke and Stephens, 2018). Involving stakeholders in the planning and execution of renewable energy initiatives can effectively mitigate social and environmental issues, guaranteeing equitable distribution of benefits (Burke and Stephens, 2018).

In summary, policy and governance are essential for attaining socioeconomic sustainability during the transition to renewable energy. Robust governance frameworks that incorporate economic, social, and environmental aspects, tackle power dynamics, and encourage stakeholder participation are crucial for cultivating an equitable and sustainable energy future.

5. EMERGING TRENDS AND RESEARCH TRAJECTORIES

The renewable energy sector is set for substantial expansion and transformation in the forthcoming decades, propelled by technological advancements, legislative initiatives, and heightened global awareness of climate change. This section examines prospective trends and research trajectories that are expected to influence the renewable energy sector. A major future trend is the ongoing decrease in the prices associated with renewable energy technology. Over the past decade, solar and wind energy have experienced significant reductions in costs, rendering them more competitive with conventional fossil fuels (Cherp et al., 2018). This trend is anticipated to persist as technical advancements and economies of scale further reduce expenses. Research endeavours concentrate on improving the efficiency and dependability of renewable energy systems, which will be pivotal for their extensive adoption (Cherp et al., 2018).

The incorporation of renewable energy into current energy systems offers both advantages and obstacles. A prominent area of research focusses on the advancement of sophisticated energy storage technologies. Efficient storage technologies are crucial for addressing the intermittency of renewable energy sources such as solar and wind (Hansen, et al., 2019). Advancements in battery technology, including solid-state and flow batteries, are anticipated to improve storage capacity and efficiency, hence facilitating more dependable and robust energy systems (Hansen, et al., 2019).

A significant development is the digitalisation of the energy sector. Digital technologies, including smart grids, Internet of Things (IoT) devices, and artificial intelligence, are revolutionising the management and optimisation of energy systems (IEA, 2020). Smart grids facilitate real-time monitoring and management of energy flows, enhancing the integration of dispersed renewable energy sources and augmenting the overall efficiency of the energy system (IEA, 2020). Research in this domain concentrates on creating advanced algorithms and machine learning models to forecast energy demand and enhance energy distribution (Layode et al., 2024c).

The significance of policy and regulatory frameworks in facilitating the renewable energy transition is paramount. Future research will likely investigate the most efficacious policy

instruments for facilitating renewable energy uptake and ensuring an equitable transition (Sovacool et al., 2020). Policies such carbon pricing, renewable energy mandates, and subsidies for clean energy technology are crucial for fostering investment and innovation in the renewable energy sector (Sovacool et al., 2020). Furthermore, research is required to examine the social and economic ramifications of the energy transition, guaranteeing equitable distribution of gains and preventing disproportionate consequences on disadvantaged areas.

Grid integration and infrastructure development are essential focal points. With the rise of renewable energy integration, there is an escalating demand for resilient grid infrastructure capable of managing fluctuating energy inputs and maintaining a stable supply (Brown, et al., 2020). This encompasses investments in transmission and distribution networks, along with the establishment of interconnectors that enable cross-border energy exchange (Brown, et al., 2020). Research initiatives focus on enhancing grid design and functionality to facilitate increased integration of renewable energy sources.

Sector coupling, which integrates diverse energy sectors including electricity, heating, and transportation, is becoming seen as a comprehensive strategy for decarbonisation (Ahmed, et al., 2020). Sector coupling utilises the synergies among several energy sectors to enhance efficiency and diminish emissions. Excess renewable electricity can be harnessed to generate green hydrogen, which can then be employed in transportation and industrial applications (Ahmed, et al., 2020). Future study will investigate the technological and economic viability of sector coupling and its capacity to expedite the energy transition.

Natural gas and its infrastructure serve a transitional function in the renewable energy sector. Natural gas, being a comparatively cleaner fossil fuel, can function as an intermediary in the transition to a completely renewable energy system (Mac Kinnon, et al., 2018). The research is on enhancing natural gas infrastructure to facilitate the integration of renewable energy, including the utilisation of existing gas pipelines for hydrogen transportation and the creation of hybrid systems that merge natural gas with renewable energy (Mac Kinnon, et al., 2018).

The future of renewable energy is defined by ongoing technological progress, favourable policy structures, and inventive methods for energy system integration. Research initiatives should focus on addressing the outstanding difficulties and optimising the opportunities arising from the renewable energy transition. By concentrating on these domains, the international community may attain a sustainable and resilient energy future.

6. CONCLUSION

This study sought to examine the socioeconomic obstacles and opportunities associated with the renewable energy transition, offering a thorough analysis that encompasses economic, social, technological, and policy aspects. This study has achieved its aims by thoroughly analysing case studies, technology breakthroughs, and governance frameworks, providing significant insights into the complex structure of the renewable energy sector.

This study's key conclusions underscore the substantial socioeconomic advantages of renewable energy, encompassing job development, economic expansion, and improved energy security. The shift to renewable energy is essential not just for alleviating climate change but also for promoting

Advancing sustainable development and enhancing public health. Nonetheless, the study also revealed significant constraints, including elevated initial capital expenditures, social and cultural impediments, and governmental and regulatory obstacles. Confronting these difficulties necessitates a synchronised approach that amalgamates technical advancement, robust policy structures, and participatory governance.

Technological innovations in renewable energy have been crucial in decreasing costs and enhancing efficiency, rendering renewable sources more competitive with conventional fossil fuels. The advancement of energy storage systems, intelligent grids, and sector-coupling technologies is essential for addressing the intermittency of renewable energy and maintaining a steady energy supply. The study underscored the significance of legislative assistance and international cooperation in expediting the transition to renewable energy.

This study's conclusion emphasises the need for a comprehensive approach to the renewable energy transition. Policymakers, industry stakeholders, and civil society must collaborate to establish a conducive environment that fosters innovation, mitigates socio-economic inequalities, and guarantees an equitable transition for all communities. Future research should focus on investigating more effective policy tools, advancing technology solutions for energy storage and grid integration, and improving public engagement tactics to foster social acceptability of renewable energy initiatives.

This paper presents a comprehensive framework for comprehending the intricate dynamics of the renewable energy transition, providing practical insights and recommendations to inform future endeavours towards a sustainable and equitable energy future.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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PROSPECTS, CHALLENGES AND OPPORTUNITIES IN THE DEPLOYMENT OF SOLAR PHOTOVOLTAICS IN DEVELOPING COUNTRIES

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ABSTRACT

The rising worldwide energy demand and the pursuit of sustainable development have resulted in the use of solar photovoltaic (PV) technology as a viable alternative. Developing nations, facing various challenges and ambitions, are at a critical crossroads where the adoption of solar photovoltaic technology might instigate significant transformation. This study examines the implementation of solar photovoltaics in developing nations, focussing on the associated problems and potential. This study examines the status of solar photovoltaic technology, the challenges it faces in developing nations, and the potential opportunities and uses. Developing countries are poised for a significant opportunity in the shift to sustainable energy. International assistance, encompassing loans, grants, technical support, and collaborative partnerships, serves as a beacon of hope, igniting the impetus necessary to promote the use of solar photovoltaic (PV) technology. The essential function of international collaboration in advancing solar energy deployment, based on case studies that illustrate the capacity for cooperative initiatives to accelerate development and foster a cleaner, more equitable energy landscape. Nigeria energy landscape is unpredictable and unreliable and so the deployment of renewable energy can ensure constant energy supply. Tanzania exemplifies how the desire for energy solutions may stimulate innovation. Haiti, a nation grappling with energy poverty, exemplifies the necessity of international collaboration for sustainable development. The Solar Market Gardens initiative was initiated by the Solar Electric



Light Fund (SELF) in partnership with local organisations and international financiers. This initiative enhanced agricultural output in Nigeria.

1. INTRODUCTION

The investigation of renewable energy sources has become an essential pursuit in an age marked by a continuous increase in global energy consumption and a pressing need for sustainable development (Kenu, 2020). Solar photovoltaic (PV) technology has emerged as a promising alternative, poised to transform the energy landscape with its abundant and environmentally friendly characteristics (Nimay et al., 2021). This paper explores the captivating realm of solar PV adoption, focussing on its advantages and problems for poor countries (Carvalho, 2021).

The significant increase in global energy consumption poses a serious concern for both the present and future (Pratish, 2021; Dania, 2020). This insatiable demand for energy, primarily driven by limited fossil fuel reserves, fosters economic growth while underscoring the essential need for energy diversification. Simultaneously, the demands of sustainable development, echoing through international channels, necessitate a departure from the established carbon-intensive path (Haris and Sarwar, 2013).

Figure 1 illustrates the two categories of energy sources: renewable and non-renewable energy. The global shift away from non-renewable energy sources, such as petroleum (Ukoba et al., 2011), is driven by their contribution to greenhouse gas emissions that exacerbate global warming. Renewable energy serves as a crucial lifeline at this critical moment, with solar photovoltaic technology assuming a dominant role. Additional forms of renewable energy encompass wind (Ukoba et al., 2023), hydro (Adhikari et al., 2023), and biomass (Imoisili et al., 2014).

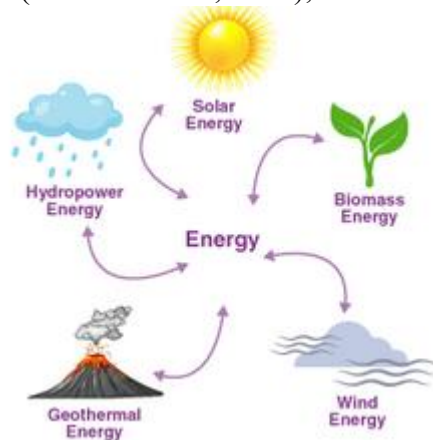


Figure 1. Sources of energy

2. SOLAR PHOTOVOLTAIC TECHNOLOGY

Photovoltaics, sometimes abbreviated as PV, derives its name from the process of turning light (photons) into electricity (voltage), known as the photovoltaic effect. Solar photovoltaic technology, predicated on the principle of converting sunlight directly into electricity, possesses an unmistakable allure. There are three primary categories of solar photovoltaic systems: grid-tied, hybrid, and off-grid. Every category of solar panel system possesses distinct advantages and disadvantages, ultimately depending on the customer's objectives for their solar panel installation.

Figure 2 illustrates thin film, monocrystalline, and polycrystalline solar panels. Solar photovoltaic systems typically comprise six distinct components: the solar PV array, a charge controller, a battery bank, an inverter, a utility meter, and an electric grid. The proper installation of all

components dictates the efficiency of the solar system solution. Solar energy can be categorised into two classifications based on the conversion method and the type of energy produced. Passive solar energy and active solar energy pertain to the methods of conversion, including solar thermal energy, photovoltaic solar power, and concentrating solar power.

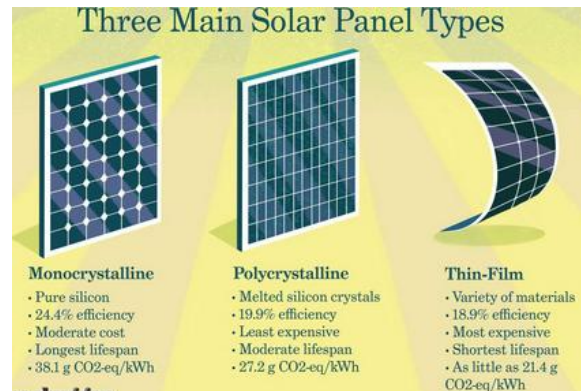


Figure 2. Categories of Solar Photovoltaic Systems

This technology holds significant potential in the sunlit regions of developing nations (Abdelrazik et al., 2022), heralding a new era of energy production. The inherent availability of solar radiation in these regions signifies the potential for energy democratisation, liberating marginalised communities from the limitations of energy poverty (Shafqat et al., 2018). Remote communities and urban slums can both benefit from electrification, igniting progress and enhancing human welfare with the sun as a universal ally.

The environmental significance of solar photovoltaic technology cannot be overstated. Its operation is remarkably discreet, generating no emissions while alleviating the suffering of the planet. As developing nations endeavour to circumvent the detrimental growth trajectories of their industrialised counterparts, solar photovoltaic technology emerges as an essential instrument (Nogin et al., 2023). This technology exemplifies responsible development, ensuring that the quest for prosperity does not adversely affect the fragile ecosystems that support life (Wyllie et al., 2018).

Developing nations are essential to the transition in the possibilities offered by solar photovoltaic technology. Countries like South Africa have commenced the implementation of solar photovoltaic systems for power generation in both rural and urban areas, as illustrated in Figure 3.

The intersection of three crucial elements—energy deprivation, carbon output, and economic progress—renders solar PV implementation a highly advantageous pursuit. The memoirs of energy poverty are characterised by themes of despair—communities languishing in darkness, lacking fundamental comforts and opportunities (Victoria et al., 2021). Nevertheless, amidst this sorrow, solar photovoltaic technology emerges as a beacon of optimism. Its decentralised nature facilitates the establishment of microgrids that traverse hazardous landscapes, illuminating lives and fostering developmental progress (Islami et al., 2021; Yoldaş et al., 2017).



Figure 3. A solar panel on a rooftop in a Nigerian House

The issue of carbon emissions, which pervades the global climate change discourse, is countered by solar photovoltaic technology. As these nations navigate the delicate balance between development and environmental conservation, solar photovoltaic technology emerges as a viable answer, enabling a reduction in carbon emissions without hindering progress. Moreover, the allure of economic growth, which serves as the foundation for the objectives of emerging nations, has unexpectedly aligned with solar photovoltaic technology. The capacity for job creation along the value chain, encompassing production, installation, and maintenance, redefines the parameters of prosperity (Bunda et al., 2023).

Moreover, significant solar PV implementation is accompanied by a multitude of challenges that require advanced solutions. Underdeveloped nations face considerable financial constraints, making the substantial initial expenses of solar systems a notable impediment (Varun et al., 2016). Moreover, the deficient grid infrastructure, characterised by fragility and volatility, necessitates substantial enhancements to support the influx of solar energy. Another concern is the complexity of regulations and procedures, which requires coordinated efforts to create an environment conducive to solar investment. Moreover, an absence of technical skills engenders a dire circumstance, underscoring the necessity for capacity-building to effectively harness solar potential (Wim and Smeets, Anse, 2022).

Nonetheless, the realm of solar PV development in developing countries is an enticing area where potential and challenges intertwine intricately. The context of this narrative encompasses the escalating global energy need, the necessity for sustainable development, and the transformative potential of solar photovoltaic technology. This article will elucidate the array of challenges that obscure this promise, intertwined with the vibrant opportunities that serve as navigators towards a more sustainable future.

In the initial phases of solar PV adoption, financial obstacles hinder extensive implementation. Resource limitations, infrastructural limits, and policy and regulatory impediments complicate solar PV implementation. Instances from Sub-Saharan Africa, the Caribbean, and South Asia illustrate hybrid solutions, intelligent grid systems, and microgrids that surmount infrastructural constraints.

Policy and regulatory impediments exacerbate the challenges of solar PV implementation. Private investments may be hindered by erratic legislation, bureaucratic obstacles, and an absence of enabling frameworks. Nonetheless, unequivocal and consistent regulatory frameworks are essential for the advancement of solar energy. Adequate technical expertise is essential for the effective design, installation, and maintenance of solar photovoltaic systems. The trajectory of solar photovoltaic adoption is significantly shaped by perception and awareness. Misunderstandings regarding the reliability, cost, and advantages of solar energy might hinder progress. Solar photovoltaic technology enhances energy accessibility, fosters employment growth, provides environmental benefits, stimulates technological innovation, and promotes global cooperation. It delivers dependable power to remote and underprivileged regions using decentralised solutions, off-grid technologies, and innovative financial structures, thereby enhancing education, healthcare, and overall well-being. Technological innovation is fundamental, illustrating how the constraints of solar adoption catalyse creative solutions. Localised technologies, smart grids, and microgrids are transforming energy landscapes, especially in regions with varied energy requirements. International assistance through grants, loans, technical support, and partnerships offers crucial support to developing nations striving to implement solar energy.

The transition to solar PV adoption in developing nations is characterised by a myriad of challenges, opportunities, and ambitions. This study explores various financial limitations, infrastructure challenges, policy obstacles, technical skill deficiencies, and perception problems, illustrating solar energy's transformative potential in terms of energy accessibility, employment generation, environmental conservation, technological advancement, and global support. The adoption of solar PV serves as a beacon, guiding the development of resilient, empowered, and equal societies in the developing countries.

2.1 Current Position of Solar Photovoltaics

The ultimate goal of green economy advocates is for solar photovoltaic technology to supply energy to nearly the whole globe, as illustrated in Figure 4.

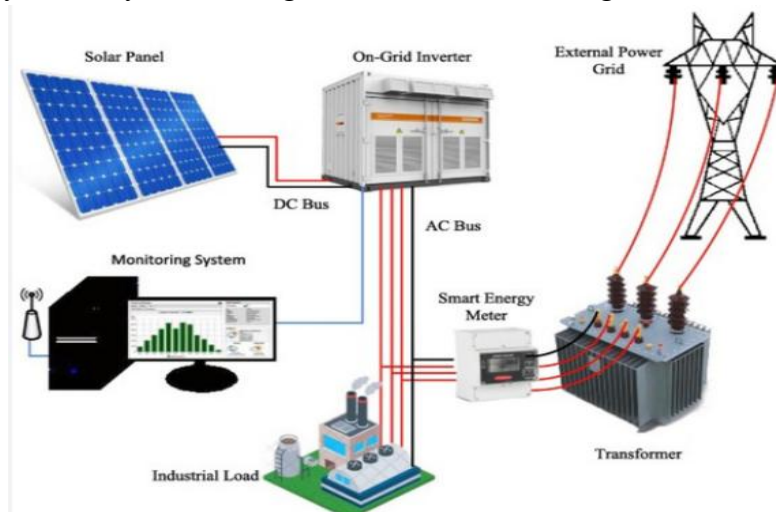


Figure 4. Application of solar photovoltaic technology for worldwide electricity production

Solar photovoltaic (PV) technology has undergone significant metamorphosis, transcending borders and altering energy landscapes globally. In the context of global challenges related to sustainable development and climate action, the status of solar photovoltaic technology stands as a symbol of optimism, reflecting both current advancements and the potential for significantly greater future accomplishments. The utilisation of solar photovoltaic technology has undergone a significant transformation in the past twenty years, evolving from a peripheral innovation to a global leader. Solar panels have first been implemented on rooftops, commercial edifices, and utility-scale installations in industrialised countries. Countries including Germany, China, the United States, and Japan have demonstrated the viability of solar energy and established a framework for developing nations to emulate (Usha and Douglas, 2011).

The status of solar photovoltaic technology is not exclusive to wealthy economies. Developing nations have enthusiastically entered the competition, driven by abundant sunlight and increasing energy requirements (Jacob, 2016). The spread of solar PV in these nations is driven by a confluence of factors, including energy access needs, economic growth objectives, and commitments to environmental stewardship. These nations are increasingly embracing solar energy to bridge energy deficits, generate employment, reduce carbon emissions, and foster technological innovation. A notable attribute of contemporary solar PV is its capacity to foster equal growth. Solar microgrids, off-grid systems, and innovative financing techniques are enhancing isolated villages, empowering individuals, and advancing education, healthcare, and overall quality of life. The integration of solar energy and technology is generating solutions that extend beyond energy accessibility, facilitating economic development while enhancing environmental sustainability (Hashwini et al., 2021).

The future of solar PV is poised for a significant transformation. The effectiveness and cost of solar panels are always enhancing due to technological advancements, rendering them increasingly accessible. Energy storage solutions, along with advancements in battery technology, are addressing the intermittency challenge, ensuring that solar energy remains reliable even post-sunset (Mehdi et al., 2023). Smart grids, Internet of Things (IoT) connection, and decentralised energy systems indicate a future where solar energy might power not only individual homes but perhaps entire cities. The global commitment to combat climate change is elevating solar PV to prominence. International coalitions, shown as the International Solar Alliance, illustrate the worldwide commitment to advancing solar energy utilisation. Financing mechanisms and regulatory frameworks are being enhanced to facilitate solar initiatives in underdeveloped countries, reflecting an increasing recognition of solar energy's potential to advance global sustainable development.

The status of solar photovoltaic technology is at a pivotal juncture of advancement and potential. Developed nations have established the foundation, but underdeveloped countries perceive solar energy as a transformative force. The modern environment is characterised by technical progress, inclusive growth, and international partnerships, indicating a future where solar photovoltaic technology becomes a transformative influence, leading us towards a more sustainable, egalitarian, and empowered society.

2.2 Challenges of Solar Photovoltaics deployment in Developing Nations

The transition to solar photovoltaic (PV) technology in underdeveloped nations is indeed beset with challenges, with financial limitations being among the most formidable. The substantial initial expense of installing solar photovoltaic systems constitutes a significant barrier to the extensive adoption of this promising renewable energy source. Developing nations often face fiscal limitations, prioritising essential areas such as healthcare, education, and infrastructure. Consequently, allocating substantial funds for solar PV installations presents a formidable challenge.

The capital required for solar panels, inverters, and energy storage systems, while offering potential long-term advantages, presents a substantial initial expense for several individuals and governments (Moner-Girona et al., 2021). India exemplifies the financial challenges linked to the use of solar photovoltaic technology. Notwithstanding its ambitious solar objectives and extensive solar potential, the country has encountered obstacles due to fiscal constraints. The Indian solar sector heavily depended on external funding during its initial stages, as domestic financial institutions were reluctant to invest in unproven technology. The establishment of initiatives like the International Solar Alliance aims to consolidate resources and use economies of scale to reduce expenses, highlighting the collaborative strategy necessary to surmount financial challenges (Oguntuase, 2022). Bangladesh serves as another compelling illustration. The nation sought to enhance power accessibility in remote areas via its robust solar home system initiative. Notwithstanding its success, the initial investment continued to pose a challenge for numerous low-income households.

To mitigate this issue, innovative financing alternatives such as pay-as-you-go systems and microloans were implemented, enabling families to get solar energy without bearing the entire financial obligation initially. A comparable narrative is unfolding in Kenya. The elevated expense of solar systems has deterred numerous individuals from embracing the technology. Consequently, mobile payment networks facilitated the creation of pay-as-you-go models, enabling homeowners to finance their solar systems incrementally over time. This innovative strategy circumvented substantial initial costs and facilitated increased solar PV deployment, thereby enhancing energy access and fostering economic growth (Adwek et al., 2020).

The prohibitive expense of solar PV installation in developing countries constitutes a major obstacle to broader implementation. The experiences of these developing nations illustrate that innovative financial strategies, cooperative initiatives, and targeted interventions can effectively address these financial limitations (Mehdi et al., 2023). As these nations navigate their paths towards sustainable energy futures, innovation, resourcefulness, and strategic partnerships become essential allies in actualising the transformative potential of solar photovoltaic technology.

A significant obstacle to the seamless integration of solar photovoltaic (PV) systems in developing nations is the inadequate infrastructure. The nascent state of grid infrastructure, coupled with erratic power supply and inadequate storage capacity, undermines the feasibility of solar arrays. Sub-Saharan Africa exemplifies the significant infrastructural challenges that can impede solar PV implementation. The region faces challenges due to insufficient grid infrastructure, rendering the integration of intermittent solar power sources a formidable task. Nigeria faces the challenge of unreliable electrical supply due to outdated and insufficient grid infrastructure. This deficiency

hinders the seamless incorporation of excess solar energy into the grid, diminishing the advantages of solar systems and obstructing efforts to electrify rural areas (Nwaigwe et al., 2019). Haiti, situated in the Caribbean, possesses a comparable narrative. The nation's energy landscape is defined by fragile and inefficient grid systems. Despite the potential of solar PV projects, the lack of contemporary infrastructure hinders the effective integration of surplus energy into the grid (Keston, 2020).

This constraint underscores the intricate relationship between solar adoption and the pressing necessity for substantial grid enhancements. Notwithstanding its effective solar home system initiative, Bangladesh faces infrastructural challenges. The limited storage capacity of batteries is a significant challenge in rural areas where solar household systems are expanding. Consequently, solar energy remains underexploited, and its potential productive applications are impeded. To address this challenge, innovative strategies such as the implementation of energy-efficient appliances and localised microgrids have emerged, enabling communities to optimise the advantages of solar energy while navigating the limitations of inadequate infrastructure. The lack of infrastructure in developing countries hinders the effective integration of solar PV systems, necessitating the management of the intricate relationship between solar technology and the infrastructure reliant on its efficacy.

The implementation of solar photovoltaic (PV) technology in underdeveloped nations is impeded by governmental and regulatory barriers. The intricate web of conflicting regulations, onerous bureaucratic processes, and absence of conducive regulatory frameworks may undermine the potential of solar energy. Nigeria exemplifies the detrimental effects of regulatory ambiguity. The country's energy sector is governed by a complex array of regulations that allow for interpretation and create ambiguity. Consequently, prospective investors in solar projects are sometimes trapped in a maze of conflicting regulations and ambiguous administrative procedures (Haris and Sarwar, 2013). The absence of legislative clarity hinders private investment and obstructs the growth of solar PV, hampering Nigeria's advancement towards a sustainable energy future.

Conversely, Chile demonstrates the transformative effects of advantageous policy frameworks. The nation's Renewable Portfolio Standard (RPS) mandates a specified quantity of energy to be derived from renewable sources, including solar photovoltaic (PV) systems. This coherent and uniform policy not only attracted significant private investment but also propelled Chile to the vanguard of solar energy development (Chiara and Francesca, 2021). The implementation of open regulations and progressive policies fostered an environment that promoted innovation, increased investment, and expedited solar PV expansion. A further compelling illustration is the United Arab Emirates (UAE). In an area traditionally dependent on fossil resources, the UAE implemented stringent rules that facilitated the adoption of renewable energy, especially solar photovoltaic technology. The UAE created a dependable revenue source for investors by implementing feed-in tariffs and power purchase agreements (PPAs) with fixed price for solar energy, facilitating rapid growth in the solar industry. This proactive policy approach transformed the country's energy sector and illustrates the transformative potential of supportive regulations (Kılıç and Kekezoğlu, 2022). Even within a same nation, varying regulatory frameworks may yield divergent outcomes. Gujarat, India, has become a solar powerhouse, partly due to assertive legislative measures. Gujarat attracted substantial private investment and emerged as a leader in solar energy production by offering appealing incentives, streamlined approvals, and a conducive environment for solar

project development. This underscores the vital importance of policy in influencing solar PV development trajectories, in contrast to other Indian states with less favourable regulatory frameworks.

The intricate web of political and regulatory challenges constitutes a significant impediment to the widespread use of solar PV technology in developing countries. A stable, open, and supportive legislative environment could be the catalyst for solar PV adoption, drawing private investment and facilitating sustainable energy transitions. As these nations navigate the delicate equilibrium between developmental necessities and regulatory transparency, they encounter a pivotal juncture towards a cleaner, more sustainable energy future.

Moreover, a significant barrier to the extensive use of solar photovoltaic (PV) technology in poor countries is the deficiency of technical expertise. The intricate process of developing, building, and maintaining solar PV systems requires trained specialists and technicians. A deficiency in these abilities significantly hinders the effective execution of solar projects. Sub-Saharan Africa illustrates the repercussions of insufficient technological expertise. The region's ability to effectively harness the vast potential of solar energy is hindered by a deficiency of skilled professionals. Tanzania is experiencing a deficiency of skilled solar professionals. Consequently, system installations are inefficient, system longevity is diminished, and maintenance practices are inadequate. This information deficit hinders both energy accessibility and the sustained profitability of solar photovoltaic systems (Jacob, 2016).

The main challenges for renewable energy deployment in Nigeria include high upfront costs and a lack of affordable financing, inconsistent and inadequate policies, and insufficient infrastructure for integration into the grid. Other significant barriers are limited domestic manufacturing capacity, a lack of skilled technical expertise, and weak institutional capacity, which together slow down project execution.

2.3 Financial and economic barriers

- *High upfront costs:* The initial cost of renewable energy systems like solar panels is a major obstacle for many households, particularly in rural areas.
- *Limited access to financing:* There is a scarcity of capital investment, with high interest rates from commercial banks and a lack of affordable, long-term financing options.
- *Low foreign investment:* Perceived risks related to policy inconsistency, currency volatility, and the overall macroeconomic environment deter foreign direct investment.

2.4 Policy and regulatory issues

- *Inconsistent and weak policies:* There is a lack of clear, consistent, and harmonized policies, which hinders implementation and creates uncertainty for investors and stakeholders.
- *Inadequate legal framework:* The legal and regulatory frameworks are insufficient, with weak enforcement mechanisms.
- *Government support distortion:* Subsidies for fossil fuels have historically created a disincentive for renewable energy, although this is changing.

2.5 Infrastructure and technological limitations

- *Inadequate grid infrastructure:* The existing power grid is often outdated, congested, and fragile, making it difficult to integrate new renewable sources.
- *Lack of transmission and distribution:* There is a lack of the necessary infrastructure for transmitting and distributing power from renewable sources.
- *Limited domestic manufacturing:* Nigeria lacks a robust domestic manufacturing capacity for renewable energy components, forcing most to be imported, which increases costs.

2.6 Human and institutional challenges

- *Lack of technical expertise:* There is a shortage of skilled technical personnel, both in the private sector and within government agencies, to effectively manage and oversee projects.
- *Weak institutional capacity:* Fragmented governance and a lack of coordination between government bodies create bureaucratic bottlenecks and inefficiencies.
- *Limited awareness:* There is a need for greater awareness of the benefits of renewable energy at both the individual and institutional levels.

Bangladesh offers an alternative viewpoint on this matter. The scarcity of competent labour was a barrier when the nation sought to implement rural electrification via solar household systems. Owing to a scarcity of experts proficient in addressing technical challenges and delivering maintenance, installed systems were underutilised, resulting in an incomplete realisation of solar energy benefits. The necessity of investing in capacity building became evident as the demand for skilled human resources became apparent (Amit et al., 2022). The International Solar Energy Society (ISES) has recognised a prevalent issue in numerous developing nations: a lack of specialised training programs and educational initiatives to foster solar expertise. The absence of comprehensive training not only constrains the advancement of solar workers but also sustains a cycle of underdeveloped solar projects.

Conversely, Morocco exemplifies progress in bridging the technical competence gap. The country acknowledged the necessity of cultivating a skilled solar workforce as it initiated substantial solar projects such as the Noor Ouarzazate Solar Complex. Morocco established training programs and knowledge-sharing initiatives in partnership with international entities and organisations. These programs empowered Moroccan technicians and engineers, facilitating the successful completion of large-scale solar projects and establishing Morocco as a leader in solar energy development.

The deficiency of technical skills constitutes a significant obstacle to solar PV advancement in poor nations. As nations navigate the challenges of solar technology implementation, investing in skilled personnel acts as a beacon, illuminating the path towards sustainable energy futures and ensuring the long-term success of solar photovoltaic projects.

An unseen yet formidable barrier to the adoption of renewable energy, especially in developing countries, is perception and knowledge. In contrast to conventional energy sources, the feasibility of solar energy as an alternative may be hindered by insufficient awareness of its advantages or misconceptions regarding its reliability and cost (Bernadette and Michael 2016). Pakistan serves as a compelling case study illustrating the impact of perception. Scepticism regarding solar energy often prevails in regions where conventional energy sources, such as fossil fuels, have been historically predominant. Pakistan's dependence on imported fossil fuels has led to ongoing power

shortages, prompting the government to promote solar energy alternatives. Nonetheless, many elements of the populace remained suspicious owing to a lack of comprehension regarding advancements in solar technology and its capacity to address energy shortages (Millison et al., 2022). In response, the government initiated public awareness campaigns, highlighted successful solar installations, and informed locals about the advantages of solar energy. This initiative to alter perception fostered a more conducive environment for solar PV adoption.

Brazil elucidates the intricate relationship between perception and the use of solar energy. Numerous indigenous communities in the Amazon rainforest lack access to reliable electricity sources. Notwithstanding its potential to provide clean and sustainable energy, solar power is regarded as an impractical luxury. Non-profit organisations and governmental initiatives intervened to enhance awareness, demonstrating the feasibility of solar systems in these remote locations. They transformed solar energy from a theoretical notion into a viable remedy for energy poverty by dispelling misconceptions and showcasing concrete benefits. Nepal illustrates the transformative effect of public awareness campaigns. The country's challenging topography and various settlements rendered typical grid extension problematic. Nonetheless, insufficient understanding regarding the feasibility of solar technology resulted in resistance in specific regions. In response, the government and non-governmental organisations (NGOs) initiated educational programs illustrating how solar photovoltaic installations may provide dependable electricity in remote areas. Local communities adopted solar systems as awareness increased, leading to enhanced living conditions and economic opportunities (Mainali et al., 2014).

A prominent instance from Bangladesh illustrates the importance of public-private collaboration in transforming perceptions. The Grameen Shakti initiative pioneered solar household systems in rural areas. The project first faced suspicion due to the prevailing belief in centralised control; hence, it commenced with a comprehensive awareness campaign. Grameen Shakti facilitated discussions, challenged preconceptions, and provided practical demonstrations of the benefits of solar energy in partnership with local leaders and communities (Amin and Langendoen, 2012). This community engagement transformed perceptions, rendering solar energy a more attainable and valued resource.

The use of solar photovoltaic technology in underdeveloped countries is greatly affected by perception and awareness. Collaborations, educational initiatives, and public awareness campaigns can bridge knowledge gaps, dispel misconceptions, and transform perceptions of solar energy (Yousaf et al., 2021). Comprehending the significance of perception and awareness is essential for realising the vast potential of solar photovoltaic technology as countries transition to sustainable energy sources.

2.7 Solar Companies in Nigeria

There are numerous solar companies in Nigeria, however, for the sake of this article, we will be looking at the 20 best solar companies in Nigeria.

a. GVE Solar Company in Nigeria

Green Village Electricity (GVE) Projects Limited is the foremost and most innovative renewable energy solutions provider in West Africa, registered with the Corporate Affairs Commission of Nigeria (RC1071222).

Through the expertise and dedication of our board of Directors, management, employees, and various business associates, we have been able to position the company as the leader in Nigeria's renewable energy industry creating value for our numerous clients through world-class service delivery with a touch of unique local contexts.

Residential Solar Solution:

- Tailored installations for homeowners to harness solar power, reduce electricity bills, and transition away from traditional power sources.
- Customized designs using high-quality materials for optimal energy production and sustainability.
- Expert guidance and exceptional customer service to ensure a seamless transition to renewable energy for a brighter future.
- Commercial & Industrial Solution:
- Innovative solar solutions for businesses and industries, from small enterprises to large industrial operations.
- Custom-designed systems by solar experts to maximize energy efficiency and cost savings.
- Focus on quality, reliability, and customer satisfaction throughout the installation process to unlock the full potential of solar power for businesses.

Rural Electrification Solution:

- Eco-friendly solar-powered solutions to provide reliable electricity to underserved rural areas worldwide.
- Community-centric approach working closely with local leaders to design and implement customized solar solutions.
- Commitment to making clean energy accessible as a basic human right to power up rural communities and improve lives.
- Utility Management and Smart Metering Solution:
- End-to-end metering solution addressing utility management challenges in emerging markets.
- Smart metering infrastructure including AMR/AMI, smart vending system, metering data management system, and STS code management system.
- Empowering clients to make smart financial and environmental choices through solar energy investment.

Other Services:

- Consultancy Services: Expert advice and guidance on solar energy implementation and optimization.
- Solar Street Lighting: Solar-powered lighting solutions for streets and public areas.
- Renewable Energy Products Sales: Sales of a variety of renewable energy products.
- Energy Auditing: Assessments and recommendations for energy efficiency improvements.
- Training: Educational programs to empower individuals and organizations with knowledge about renewable energy technologies and practices.

b. Arthur Energy Technology Limited

Arthur Energy Tech Ltd is one of the few solar companies in Nigeria situated in Isolo. It is a solar company that has grown in prominence in the solar energy industry as a result of previous projects completed.

They also manage their services throughout Lagos. They are well-known for supplying and installing solar panels with unit standards for street lighting, agricultural lighting, boreholes, houses, schools, and businesses.

c. Energy Excel Systems and Solutions Limited

Energy Excel systems and solutions Ltd is an Abuja-based firm that sells, maintains, and installs deep cycle batteries, solar inverters, and UPS systems. In addition, the Abuja-based firm sells, installs, and maintains unit-specific solar goods such as solar traffic lights, solar street lamps, and solar submersible water pumps.

d. Enerplaz Renewable Energy

This is one of the few solar companies in Nigeria situated in Port Harcourt that specializes in solar products and services. They sell, distribute, and install solar inverters, batteries, and panels in homes, industries, businesses, and commercial settings.

e. Novel Power Systems

Novel Power Systems, located in the old city with brown rooftops, Ibadan, is a leading solar company in the ancient city and Oyo state. The Ibadan-based solar company sells, installs, and maintains solar inverters and batteries for homes, schools, factories, and commercial sectors.

f. Pamtronics Nigeria Limited

The Ikeja-based solar enterprise offers solar energy equipment sales, consults, and installations. They are largely focused on the installation of solar thermal systems and photovoltaics (PVs).

g. BETSAM Engineering Services

BETSAM engineering, located in the world-famous Ikeja Computer Village, is a solar company that handles the sales, installation, and maintenance of solar energy equipment in and around Lagos. The Ikeja-based solar company sells and installs solar panels, backup systems, and solar batteries for homes, businesses, ATMs, security lights, and data servers.

h. Rose Top Nigeria Limited

Rose top Nig. Ltd is a Lagos-based solar firm that specializes in solar energy product advice, sales, installations, and service for private and public clients. The Lagos-based company also installs, refines, and services petrol and diesel generators. Similarly, the company rents out generators to individuals. Rose Top is the 8th best among the various solar companies in Nigeria

i. Green Energy

Green Power, regarded as Nigeria's greatest solar enterprise, was created in 2006 and is focused on providing dependable, intelligent energy solutions using [renewable energy](#). The company's mission is to deliver energy conservation that is both environmentally beneficial and cost-effective. You may be assured of timely service delivery if you choose green electricity, owing to a highly dependable management and technical team. They have also built a good reputation over the years by providing services to individuals, telecommunications companies, private enterprises, schools, hotels, and hospitals, among others. They provide electrical installation services, as well as solar energy systems, solar thermal energy systems, backup inverter systems, and energy consulting.

j. Ecozar Technologies Inc

Ecozar Technologies is a company that offers excellent solar services at a cheap price. This is especially true when it comes to providing, installing, and maintaining high-quality solar systems and inverters. This company, launched in 2014, is a national leader. They are professionals in the installation of inverters and [solar power](#) systems in homes and businesses across the country. Ecozar Technologies also provides flexible service to customers in order to create strong customer connections. The routine follow-up examinations are also extremely nice. The company ensures that consumers receive the best solar installations possible.

k. Hians Energy Solutions Limited

Another prominent solar firm in Nigeria is Hians Energy, which specializes, among other things, in electrical wiring and the installation of renewable energy sources such as solar power. Because of their extremely competent technical team, you may be confident that you will receive the best. This is especially true when it comes to building a backup power inverter, getting solar power advice, and getting electrical services. You can talk to them about how many batteries or solar panels you'll need for your tiny house.

l. LEKS Environmental Limited

Leks is another well-known solar and renewable energy company in Nigeria. The company has made a name for itself in the energy industry. Since its inception in 2011, Leks Environmental Limited has become known for its sustainable energy and safety solutions. They also sell garbage and recycling equipment, medical emergency transportation services, and health and safety items. They also construct environmental and energy infrastructure.

m. Infinite Solar Solutions Nigeria Ltd

Infinite Solar Solutions Nigeria Limited is another reliable and fairly priced solar energy provider in Nigeria. They provide competent customer service personnel who help clients understand their needs. Importation, wholesale, and retail of solar products are other areas of specialization for Infinite Solar. They can put in solar street lights, hybrid and standalone inverters, solar lights, garden lights, solar refrigerators, solar panels, LED lights, and other things.

n. Solar Force Nigeria Plc

Solar Force Energy is Nigeria's most dependable renewable energy company. The company was created in 2007 and is dedicated to providing the general population with access to the most advanced solar technology available. SFN is a division of Solar Force Corporation in the United States. They offer genuine products such as Solar Streetlights, Mini Grids, Solar Boreholes, and others.

o. Wavetra Energy Limited

Wavetra Energy LTD is one of the best companies to work within the solar energy industry. Over the years, they have helped customers install a variety of solar energy technology, including solar panels, charge controllers, inverters, and deep-cycle batteries. In addition, Wavetra Energy LTD sells authentic LED bulbs, windmills, solar street lights, and related accessories.

p. Astrum Energy Solutions Ltd

Astrum Energy Solutions offers full-time solar renewable energy services. This solar company was founded in 2007. They install solar PV systems in homes, companies, and even entire towns. Customers that use this company rave about them. Astrum Energy Solutions Ltd has offices in Lagos, Port Harcourt, and Jos. You may count on them to provide timely and dependable renewable energy services. They also provide warranties for their solar services.

q. Rubitec Nigeria Limited

Rubitec Nigeria Ltd. is a famous solar energy company in Nigeria. The group provides backup choices for offices as well as different power sources for residences. This solar backup can power your appliances. Rubitec Nigeria also offers and installs farm agro-solar systems, biomass energy systems, and mini-grid systems. They provide services to both urban and rural communities in Nigeria.

r. Powertech Solar Energy Ltd

Powertech Solar Energy is well-known for supplying high-quality solar-powered products for your homes, companies, and industrial settings. This company was founded in 2010. It distributes solar things in quantity, large equipment, portable hybrid rooftop systems, solar energy equipment, and other items quickly and easily throughout Nigeria.

3. OPPORTUNITIES AND APPLICATIONS OF SOLAR ENERGY

The consistent availability of reliable power is a fundamental aspect of global advancement. However, this connection remains tenuous for numerous underdeveloped and rural regions in rising nations. Solar photovoltaic (PV) technology is emerging as a transformative force that offers a unique opportunity to enhance this fabric by illuminating the lives of individuals in areas previously unserved by modern energy sources. The significance of solar PV in addressing electrical poverty is exemplified by the dramatic case of Sub-Saharan Africa. This region continues to have millions of individuals lacking access to electricity, thereby constraining opportunities for progress. Rwanda exemplifies transformation. The Rwandan government collaborated with international partners to deploy decentralised solar systems, emphasising off-grid solar solutions (John et al., 2011; Adedeji et al., 2023). This collaborative initiative ignited educational empowerment while illuminating remote residences. The opportunity for pupils to study at night significantly enhanced their academic prospects and fostered a culture of learning. Similarly, solar photovoltaic energy has initiated a new era of possibility in central India, where millions reside in rural darkness. Dharnai village in Bihar exemplifies the transformative potential of solar microgrids on communities. The community had a prolonged absence of electricity for decades, hindering economic advancement and limiting access to healthcare services. The construction of a solar-powered microgrid revitalised the neighbourhood. With the illumination now pervasive, essential services became more accessible in residences, educational institutions, and healthcare facilities. This transition vividly demonstrated the connection between solar energy and the advancement of human potential (Mathai, 2022).

Bangladesh emphasises that solar energy may surmount challenges. The solar home system initiative became a crucial support for residents in the remote areas of the expansive nation. Despite the constraints of their geographical seclusion, off-grid families today possess access to clean and sustainable energy (Millison et al., 2022). This not only improved living conditions but also

enabled the villagers to utilise solar energy for productive activities such as operating small businesses and irrigating crops. Access to electricity served as a catalyst for comprehensive advancement within the development framework. The Mali-Folkecenter Nyetaa collaboration demonstrated the reciprocal advantages of solar energy and healthcare. Vaccines and pharmaceuticals requiring constant refrigeration can now be reliably kept by implementing solar-powered refrigeration units in healthcare institutions. This initiative had extensive repercussions that transcended the health facilities, as enhanced access to healthcare led to healthier communities, reduced disease burdens, and eventually improved quality of life. In rural and undeveloped areas, solar PV lamps represent a symbol of potential, providing energy access rather than merely functioning as light sources. Outside the confines of electrified homes, the ramifications of energy availability create a fabric of empowerment, resilience, and hope. Solar photovoltaic technology acts as a conduit to a more equitable and affluent future as developing countries strive to overcome the energy divide.

Moreover, the implementation of solar photovoltaic (PV) technology in renewable energy is not merely a transition to sustainable power; it also serves as a catalyst for economic transformation. The capacity of solar PV adoption to generate diverse employment opportunities along the whole value chain is one of its most attractive attributes. The significant impact of solar energy on job creation, encompassing manufacturing, installation, maintenance, and research, offers hope, especially for developing countries (Zhuo et al., 2021). An exemplary demonstration of the employment potential of this technology is evident in China, the global leader in solar PV installations. The country's industrial sector achieved unprecedented success due to its ambitious solar objectives. In response to the demand for solar panels, manufacturing hubs were formed, resulting in a significant increase in employment opportunities in production, quality control, and research and development. This substantially facilitated economic expansion and enabled millions to transcend poverty by generating stable employment opportunities.

Germany exemplifies the influence of solar PV adoption on employment. The expansion of the solar business was catalysed by the nation's unwavering dedication to the "Energiewende," or transition to renewable energy. Employment opportunities were generated in significant quantities, ranging from small-scale solar farms to extensive rooftop solar systems. With the expansion of the solar business, employment opportunities for engineers, technicians, sales personnel, and administrative staff flourished (Shaughnessy 2022). This surge in employment expansion permeated several areas of the economy, fostering a sense of sustainable development and collective empowerment. Kenya exemplifies a noteworthy case from the African continent. Local solar enterprises specialising in both off-grid and grid-connected systems were formed due to the Kenyan government's initiative to increase solar energy utilisation. Consequently, roles spanning from sales and marketing to technicians specialising in solar systems were established. Both urban and rural areas capitalised on these employment opportunities, contributing to the nation's economic advancement and poverty alleviation initiatives (Ditlev-Simonsen, 2022).

The solar home system initiative in Bangladesh promoted self-employment and entrepreneurship. Solar household systems were installed and maintained by locally trained technicians, creating a network of professionals that enhanced electricity access and stimulated local economies. The expansion of the solar sector cultivated an ecosystem of suppliers, instructors, and technicians, illustrating how solar energy may promote a broad labour market. The use of solar PV technology

acts as a catalyst for employment expansion throughout the value chain. Solar photovoltaic technology presents significant opportunities for substantial employment and aids in achieving sustainable development objectives as developing countries seek to enhance economic growth and alleviate poverty (Thilanka et al., 2021).

Solar photovoltaic (PV) technology emerges as a beacon of hope in the face of pressing global environmental concerns, serving not only as an energy source but also as a pathway to environmental restoration and sustainable development. The environmental benefits of solar photovoltaic technology significantly impact climate change mitigation and the attainment of sustainable development objectives, as it can substitute fossil fuels and diminish carbon emissions. Germany is a resolute advocate for the environmental benefits of solar photovoltaic technology. Substantial decreases in greenhouse gas emissions were attained due to the nation's considerable investment in renewable energy, particularly solar power. Germany achieved significant advancements in reducing its reliance on fossil fuels when the proliferation of solar panels occurred. This alteration not only facilitated a more sustainable energy composition but also positioned the nation as a global frontrunner in the utilisation of renewable energy sources (Shaughnessy, 2022).

In Costa Rica, solar energy generation and environmental conservation coexist together. The country's commitment to sustainability allowed it to generate 100% renewable energy for prolonged durations. Costa Rica diminished its reliance on foreign fossil fuels while concurrently lowering carbon emissions by using its abundant solar energy. This remarkable accomplishment demonstrated the capacity of solar photovoltaics to foster sustainable growth while conserving natural resources. China, often associated with rapid industrialisation and environmental challenges, shows the transformative potential of solar photovoltaic technology. The rise in solar installations resulted from the nation's efforts to transition to more sustainable energy sources. This significant transformation substantially aided worldwide initiatives to alleviate climate change while enhancing air quality and decreasing reliance on coal (Millison et al., 2022). The pivotal importance of solar photovoltaic technology in shaping a sustainable future is evidenced by China's transition from the foremost emitter of greenhouse gases to a frontrunner in renewable energy (Adelakun and Olanipekun, 2019).

The Noor Ouarzazate Solar Complex in Morocco exemplifies the potential of solar energy for environmental conservation. The complex, among the largest solar power facilities globally, reduces Morocco's dependence on fossil fuels and thereby diminishes carbon emissions. This modification aligns with the nation's commitment to reduce its carbon footprint and bolster global initiatives to address climate change (Mohamed and Touhami, 2020). The adoption of solar PV technology exemplifies human ingenuity in enhancing our relationship with the environment, beyond mere electricity generation. Solar photovoltaic technology (PV) represents a promising solution as the world grapples with the challenges of climate change and sustainable development, offering a viable method to reconcile expansion with environmental stewardship.

Moreover, solar photovoltaic (PV) technology is crucial in the integration of renewable energy sources, as it addresses pressing energy challenges while simultaneously providing a platform for innovation. The challenges faced in the use of solar energy in poor countries serve as a catalyst for innovative solutions. The challenges of solar adoption drive technological innovation, shaping the

path towards cleaner, more sustainable energy futures (Dirk and Sven, 2021). These breakthroughs encompass pioneering technology, creative financial frameworks, and tailored commercial solutions.

Bangladesh exemplifies a remarkable case study of technical innovation arising from adversity. The country's highly populated metropolitan centres encountered significant challenges in the development of solar power due to insufficient available space. In response, enterprises developed innovative solutions such as rooftop solar systems and solar-powered charging stations (Huang, 2021). These specialised, advanced approaches, tailored for urban environments, not only improved solar implementation but also facilitated increased access to electricity. Kenya exemplifies how technology can address challenges associated with conventional infrastructure, particularly in areas where isolated populations often lack access to energy. The advent of mobile payment networks facilitated innovative financing models for solar energy. Pay-as-you-go solutions enabled families to finance solar systems incrementally, despite the absence of upfront capital. The convergence of technology and capital changed energy availability, showcasing the transformative potential of innovation (Marina et al., 2020).

Technology-driven solutions have been essential in addressing challenges in India, a country distinguished by its diverse energy landscape. The advancement of solar-powered microgrids has proven essential in providing electricity to remote villages and underserved regions. When integrated with smart grid technology, these decentralised systems offer specialised solutions that transcend the limitations of traditional infrastructure development and ensure reliable energy availability (Shaughnessy 2022; Acosta et al., 2016). Tanzania exemplifies how the desire for energy solutions may stimulate innovation. The deficiency of access to modern energy services in remote areas necessitated novel solutions. Companies developed portable solar-powered lanterns and home systems, transforming illumination and communication in off-grid communities. These technological breakthroughs facilitated innovative methods for communities to harness solar energy, whilst serving as a crucial source of electrical access. The challenges of deploying solar PV in impoverished nations are not insurmountable barriers; instead, they act as catalysts for technological progress. Technological innovation serves as a beacon, illuminating a path towards a more sustainable and equitable energy future as the world confronts the obstacles of transitioning to cleaner energy sources.

In conclusion, developing countries are poised for a significant opportunity in the transition to sustainable energy. International assistance, encompassing loans, grants, technical support, and collaborative partnerships, serves as a beacon of optimism, igniting the impetus necessary to promote the use of solar photovoltaic (PV) technology. The essential function of international collaboration in advancing solar energy deployment, as evidenced by case studies that illustrate the capacity for cooperative initiatives to accelerate development and foster a cleaner, more equitable energy landscape (El-Haggar and Samaha, 2019).

International aid has catalysed the use of solar energy in Sub-Saharan Africa, creating a poignant context for this advancement. A prime illustration is the International Finance Corporation's (IFC) Scaling Solar initiative. This program promotes public-private partnerships to optimise project development processes and attract private investment in countries such as Zambia and Senegal. International groups establish the foundation for solar initiatives that enhance energy availability

and stimulate economic development by providing technical expertise, aiding regulatory frameworks, and mobilising financial resources. Haiti, a nation grappling with energy poverty, exemplifies the necessity of international collaboration for sustainable development. The Solar Market Gardens initiative was initiated by the Solar Electric Light Fund (SELF) in partnership with local organisations and international financiers. This initiative enhanced agricultural output and elevated living standards through the implementation of solar-powered water pumps, drip irrigation systems, and educational programs. These collaborative endeavours demonstrate that global aid can extend beyond energy accessibility and catalyse additional advancements.

The International Solar Alliance (ISA) exemplifies the collaboration between developed and developing countries. The ISA unites countries to address challenges related to solar energy development, aiming to mobilise over one trillion dollars in investments for solar projects by 2030. This initiative was spearheaded by France and India, demonstrating how global cooperation can catalyse the growth of the solar sector. The Green Climate Fund (GCF) exemplifies the commitment of multinational groups to advancing solar energy utilisation. The GCF provides financial and technical assistance for climate mitigation and adaptation programs in impoverished countries. The GCF endorses solar initiatives such as Uganda's Rural Electrification Programme, promoting energy accessibility and aligning with broader sustainable development objectives. The objectives of developing nations are linked to the expertise and resources of the global community through foreign assistance, which acts as a conduit. International collaborations illuminate the path, fostering resilience, strengthening communities, and establishing a shared direction towards a more sustainable and inclusive world as developing nations navigate the arduous journey towards cleaner energy futures.

4. RECOMMENDATIONS

As solar PV adoption expands in developing nations, numerous recommendations arise as guiding principles for a more effective and equitable transition:

- a) Governments ought to develop stable and supportive regulatory frameworks that promote private investment, innovation, and local entrepreneurship. Well-defined policy frameworks, incentives, and efficient approval processes can substantially expedite the deployment of solar photovoltaic technology.
- b) Capacity Building: To address the deficiency in technical abilities, it is imperative to finance training programs, educational initiatives, and skill development. Sustained success relies on empowering local communities with the knowledge and skills necessary for solar PV installation, maintenance, and management.
- c) Innovative Financing: For resource-constrained areas, solar PV systems may be economically viable through microloans, pay-as-you-go strategies, and public-private collaborations. Financial aid could be further enhanced through collaboration with international financial institutions and organisations.
- d) Awareness and Education: Educational programs and public awareness campaigns elucidate misconceptions, enhance knowledge, and cultivate a culture of acceptance for solar energy. The broader adoption of solar technology may be promoted by presenting tangible examples of its benefits.

- e) The significance of foreign aid cannot be overstated in joint projects. Collaborations with international groups and partnerships between developed and developing nations can furnish resources, expertise, and impetus for solar energy initiatives.

In conclusion, the trajectory towards the adoption of solar photovoltaic technology in impoverished nations is fraught with possibility, promise, and a necessity for concerted efforts. The challenges faced are not impediments to overcome, but rather catalysts for innovation and progress. We can forge a path to a more sustainable, equitable, and robust future for everybody by harnessing the promise of solar energy. Collaborative efforts across governments, organisations, communities, and individuals contribute to a narrative of transformation, resilience, and hope that transcends national boundaries and shapes the trajectory of the world.

5. CONCLUSION

The path to solar photovoltaic (PV) adoption in developing countries is a challenging aspect of global development, characterised by difficulties, achievements, and boundless potential. Upon examining the various aspects of this project, it is evident that, despite the obstacles present, opportunities and potential remain, facilitating a future with cleaner, more sustainable energy sources.

The challenges encountered in the deployment of solar photovoltaic technology, encompassing budgetary limitations, infrastructure deficiencies, and governmental obstacles, are not insurmountable. They represent the convergence of creativity, determination, and collaboration, resulting in the formation of new pathways. The financial complications that formerly hindered development are being increasingly addressed through novel financing arrangements, incentives, and cooperative investments. Infrastructure limitations have catalysed the advancement of hybrid technologies, decentralised networks, and intelligent grids, fundamentally transforming energy acquisition and utilisation. Transparent frameworks and progressive rules that acknowledge the transformative potential of solar energy are swiftly supplanting regulatory impediments.

Access to energy, job creation, environmental conservation, technological progress, and international collaboration are all promising prospects in the horizon. The unparalleled capacity of solar PV to illuminate dark areas, stimulate local economies, diminish carbon emissions, foster innovation, and establish international partnerships is noteworthy. These elements collectively present a compelling case for action and investment from individuals, governments, and organisations who see the importance of this juncture in shaping the sustainable future of our world.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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LOW-CARBON APPROACHES TO MEET NIGERIA'S ENERGY REQUIREMENTS IN ITS MIGRATION TO RENEWABLE ENERGY

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Abstract

Nigeria is at a critical crossroads: despite oil and gas earnings historically underpinning the economy, the nation endures persistent electricity shortages, significant dependence on diesel generators, and the social challenges posed by an unstable power supply. Recent policy and market indicators, such as the Energy Transition Plan (ETP), updated NDC commitments, and increasing investor interest in distributed renewable energy (DRE), present a strategic opportunity to expedite renewable energy deployment, enhance electricity access, reduce emissions, and foster resilient local economies. This study amalgamates technical, economic, institutional, and social viewpoints to delineate prioritised routes for Nigeria's low-carbon transformation. We evaluate the framework and limitations of the existing energy system by utilising evidence from scholarly research, national policy frameworks, and international assessments. We analyse the potential and deployment options for renewable resources at both utility and decentralised levels, explore financing and institutional challenges, and propose specific policy and implementation strategies. The analysis indicates that Nigeria's renewable energy resources—solar, hydro, biomass, and localised wind—are underutilised due to ongoing system instability, financial deficiencies, and gaps in policy implementation. Decentralised systems, including solar household units, mini-grids, and hybrid solutions, constitute the most economical approach to electrification and less dependence on diesel. Attaining scale necessitates the persistent execution of policies, tariff reform, blended finance, and the enhancement of skills, while safeguarding social rights and facilitating an equitable transition for regions reliant on fossil fuels. We conclude with a strategic

plan and research agenda to synchronise climate targets, investment streams, and equitable considerations in Nigeria's energy future.

1. INTRODUCTION

Nigeria, the most populous nation in Africa and its largest economy by GDP, plays a crucial role in influencing both continental development paths and the global transition from fossil fuels. Notwithstanding its substantial hydrocarbon reserves, particularly oil and natural gas, the country persists in facing an inconsistent electricity supply. The national grid persistently fails to meet demand, forcing households and businesses to rely on kerosene, diesel and petrol generators for their daily energy requirements. This contradiction of resource abundance coupled with enduring energy poverty highlights the simultaneous challenges and prospects associated with Nigeria's transition to renewable energy (Aliyu, 2015; EIA, 2023).

Nigeria has established ambitious frameworks for climate and energy transition. The Energy Transition Plan (ETP) outlines a trajectory towards achieving net-zero emissions by 2060, supported by long-term low-emission development strategies (LT-LEDS) and revised Nationally Determined Contributions (NDC) pledges from 2021, which incorporate conditional mitigation targets linked to international financing and assistance. Although these frameworks indicate ambition, substantial implementation challenges persist. Facilitating a fair and expedited transition necessitates strategies that connect Nigeria's renewable resources—solar, hydro, biomass, and decentralised mini-grids—with accessible financing, institutional reforms, and protections for communities reliant on fossil fuel industries (Energy Transition Budget analysis, 2023). This article integrates contemporary facts and policy discussions to recommend feasible transition pathways for Nigeria. It underscores decentralised renewable energy (DRE) as the most expedient and economical solution for electrification, while simultaneously accentuating the incorporation of utility-scale renewables into an enhanced infrastructure. Mitigating political economy restrictions and utilising creative financing are essential for realising a scalable, inclusive, and resilient energy transition (Akinyele et al., 2015; Chanchangi et al., 2023).

2. APPROACHES USED IN THIS STUDY

This study offers a comprehensive synthesis derived from various evidence sources: (a) peer-reviewed research on Nigeria's energy sector and renewable resource evaluations, identified through systematic searches in Scopus, Web of Science, and Google Scholar; (b) national policy frameworks and planning documents, including the Energy Transition Plan (ETP), LT-LEDS, and updated Nationally Determined Contributions (NDCs); (c) reports and technical papers from international organisations such as the IEA, IRENA, World Bank, and EIA; and (d) credible media coverage of recent developments in the sector, including grid failures, subsidy reforms, and financing initiatives. Priority is given to empirical research and reputable statistics (e.g., World Bank and IEA datasets) to guarantee credibility and policy significance. The book aims to offer a policy-oriented synthesis that integrates academic analysis, policy documentation, and international evaluations, rather than producing fresh primary data. A primary constraint is the fluidity of Nigeria's energy and policy landscape, characterised by fluctuating financial commitments and changing deployment objectives, which creates ambiguity in forecasting long-term results. The suggestions emphasise the need for institutional fortification, governance reforms, and adaptable policy frameworks capable of enduring market volatility and

political changes, while promoting an inclusive and sustainable renewable energy trajectory (IRENA, 2022).

3. The current state of Nigeria's energy system

3.1 Primary Energy Composition and Electricity Sector Framework

Nigeria's energy sector is predominantly reliant on fossil fuels. Oil constitutes the foundation of export revenues and powers transportation and small-scale electrical production, whilst natural gas is progressively recognised as a domestic transition fuel and a vital industrial feedstock. National statistics and worldwide energy profiles indicate that the country has extensive proved gas reserves, and gas-fired power has traditionally comprised a substantial portion of electrical generation. Nonetheless, persistent impediments such as pipeline outages, supply deficiencies, and plant.

Failures, vandalism, and inherent transmission deficiencies continuously diminish actual output. Despite the official documentation of installed generation capacity in the tens of gigawatts, the actual accessible supply significantly lags behind this potential. Operational inefficiencies, along with institutional and infrastructural limitations, result in inadequate per-capita electricity supply. Consequently, homes and enterprises throughout Nigeria heavily depend on decentralised diesel and petrol generators, leading to elevated energy expenses, air pollution, and susceptibility to fluctuations in fuel prices (IEA, 2024).

3.2 Access to Electricity and Reliability

Global statistics and IEA assessments underscore ongoing deficiencies in universal power access and the underutilisation of the national grid, particularly in rural areas. Data from the IEA and World Bank reveal that access improvements in Nigeria are inconsistent: urban families see comparatively greater connection rates, whilst rural communities are markedly underserved. The discrepancy is exacerbated by frequent grid failures and widespread blackouts, which diminish trust in centralised supply. The grid's instability compels extensive dependence on expensive generator fuel, escalating production costs for businesses and households, so undermining overall economic competitiveness (World Bank country due to access to electricity) (NEP/REA, 2023; ETP, 2023).

3.3 Institutional Frameworks and Historical Reforms

Nigeria's electricity system has undergone continuous reform initiatives, especially since the early 2000s, focusing on the privatisation and unbundling of generation, transmission, and distribution to entice private investment and enhance efficiency. However, ongoing institutional deficiencies, tariff shortfalls, and accrued liabilities have consistently eroded investor trust and constrained industry transformation. Recent initiatives, including the formation of the Rural Electrification Agency (REA) to promote decentralised renewable energy and mini-grid implementation, constitute essential components of current transition efforts. For these initiatives to be effective, policy frameworks must equilibrate federal and state responsibilities, guarantee transparent and competitive procurement processes, and tackle the economic sustainability of changes (UNFCCC/NDC Partnership, 2023).

4. Potential of renewable resources and present implementation

4.1 Solar photovoltaic (PV) technology

Nigeria possesses some of the greatest sun radiation levels in Africa, establishing solar photovoltaics (PV) as its primary renewable energy resource. Deployment options encompass extensive solar farms linked to the grid, rooftop photovoltaic systems catering to commercial and industrial clients, and an ever-expanding decentralised market of solar home systems (SHS) and community mini-grids. In recent years, the adoption of decentralised solutions has intensified, propelled by private sector innovation and donor-supported initiatives, with the Rural Electrification Agency (REA) significantly pushing mini-grid and solar home system (SHS) programs. However, numerous challenges remain: dependence on imported panels and system components, restricted access to affordable local financing, significant capital expenditures for utility-scale projects, and the technical difficulties of incorporating variable solar generation into an already vulnerable grid without additional investments in storage and modernisation (Pendleton et al., 2012; EIA, 2023).

4.2 Hydropower and Small Hydroelectric Systems

Hydropower in Nigeria has a longstanding history, with large-scale dams augmenting the grid, although constrained by environmental and societal factors, sedimentation, and fluctuation. Small hydro (run-of-river and mini-hydro) can be efficient in particular river basins and for localised micro-grids. Nonetheless, substantial dam projects necessitate meticulous environmental and socioeconomic evaluations, as well as money, and can require years for completion. Hydropower is essential for the seasonal stabilisation of renewable energy sources but is hindered by climate unpredictability. (EIA, 2023).

4.3 Biomass and Bioenergy

Biomass resources, such as crop leftovers, organic municipal waste, and dedicated energy crops, constitute a significant renewable energy alternative, especially for rural electrification and combined heat and power in agricultural processing centres. To optimise advantages, bioenergy efforts must confront sustainability difficulties, including food-fuel rivalry and land-use pressures, while using efficient conversion techniques such as gasification and biogas systems. Despite its current limited application in Nigeria, bioenergy presents potential within circular economy models by converting waste streams into usable energy. Analysis of the Energy Transition Budget 2023

4.4 Wind Energy

wind energy in Nigeria is significantly site-dependent, with practical potential primarily located in coastal areas and certain northern regions where wind speeds are advantageous. In contrast to solar energy, wind energy implementation has been minimal due to inadequate resource mapping, elevated infrastructure expenses, and governmental preferences favouring solar expansion. However, the integration of wind energy with solar and storage systems offers potential for hybrid solutions in regions where wind conditions are conducive to commercial-scale investment (Mohammed et al., 2013; Mwikamba, 2024).

5. POTENTIAL POF RENEWABLE ENERGY UTILISATION IN NIGERIA

Renewable energy possesses significant potential in Nigeria and might address substantial energy deficiencies in rural regions, especially in northern Nigeria. The magnitude of prospects is only now becoming evident as novel grid technologies, such as concentrated solar power, emerge as challengers to traditional power generation. Technological advancements indicate that solar power, when well financed, has the potential to revolutionise household energy requirements. Affordable compact lighting items priced below \$30 enable low-income households to benefit, however funding even minimal capital expenditures continues to be a challenge at all levels. Advancements in lighting provide potential enhancements in meeting additional requirements, owing to ongoing gains in efficiency and cost-effectiveness.

The magnitude of renewable energy potential much exceeds the awareness of the public and politicians. Recent studies reliably estimate Nigeria's concentrated solar thermal power potential to exceed 427,000 MW. Current electricity generation levels of approximately 5000MW satisfy merely a portion of demand, and renewable energy could assume an increasingly significant role. Extensive renewable energy generation has the potential to be transformative, yet small-scale consumer and household systems could provide energy autonomy for most individuals currently lacking consistent electrical access.

The experiences of a limited number of renewable energy providers in Nigeria over the past decade are essential for the development of sustainable markets. For the sector to advance, both practitioners and government must assimilate lessons on proper adaptation, service, installation, and efficiency in emerging technologies. Failing to integrate this experience poses a significant risk of perpetuating the underperformance that has led to near market failure in recent years. Significant education of consumers and officials is necessary to transform existing negative opinions into informed judgements regarding energy options.

The unit cost of renewable energy (\$0.26–0.50/kWh) significantly exceeds that of grid electricity (\$0.10–0.15/kWh), which primarily accounts for the implementation of subsidies and feed-in tariffs in numerous countries. A significant portion of international planning and incentives is centred on climate change obligations and trends, wherein the swiftly decreasing cost of renewable energy is projected to render it competitive without subsidies within ten years. In Nigeria, the immediate competitiveness of renewable energy is more probable due to the dependence on generators and kerosene, which elevates the actual cost of energy requirements in numerous regions to above \$0.50 per kilowatt-hour.

Financing for renewable energy presents a significant challenge, as the majority of expenses are borne upfront during installation. The elevated borrowing costs in Nigeria, characterised by interest rates over 20 percent, serve as a significant deterrent to energy investments that may recover expenses within relatively brief durations (about 1–3 years). This issue affects all strata—ranging from impoverished families attempting to secure \$30 for essential lights to households and enterprises requiring substantial investments amounting to thousands of dollars.

Significant advancements in energy efficiency and the affordability of renewable energy sources have resulted in a substantial reduction in the capital required for essential applications. The

adaptation of renewable energy for water boreholes, lighting, refrigeration of medical supplies, and IT applications in rural regions has swiftly become more economical. Capital investment is necessary. However, expenses have frequently decreased by over 75 percent in the past five years. Essential measures remain necessary to connect capital, market development, and reliability; yet, international expansion indicates that these measures could facilitate rapid transformations. Comprehensive reforms are essential for Nigeria to achieve its renewable energy potential. These modifications necessitate simultaneous implementation and sufficient resources. The subsequent important recommendations underscore the imperative for a comprehensive approach to transformation.

6. PRINCIPAL RECOMMENDATIONS

Formulate cohesive strategies for renewable energy planning and investment. The federal government must enhance its current activities by formulating a comprehensive renewable energy strategy and implementing a substantial increase in funding for research, market development, and regulation of renewable energy.

Facilitate incentives for the adoption of renewable energy

The government should contemplate incentives, potentially via a feed-in tariff, for at least one significant trial project of solar thermal power generating in northern Nigeria.

Guarantee enough and economical capital funding

Systematic expansion of low-interest capital finance for renewable energy is essential, with capital availability increasing in tandem with industry growth.

Enhance public comprehension of renewable energy

Stakeholders in the renewable sector and government must substantially spend in public education to enhance consumer and policy decisions and to dispel prevailing biases against the industry.

Foster cooperation between renewable energy developers and politicians

Policymakers and renewable energy stakeholders must collaborate to establish optimal service practices in rural regions, especially with education, healthcare facilities, and water supply.

Instruct on energy use and efficacy

Energy consumption, especially energy efficiency and renewable energy, must be integrated into the education system promptly to influence public behaviour and enhance engagement in the burgeoning renewable energy sector.

7. POTENTIAL FOR SUSTAINABLE ENERGY ADVANCEMENT

The prevailing view of renewable energy in Nigeria primarily emphasises solar energy, with occasional reference to wind power. Renewable energy has a rather brief history in Nigeria, particularly in the public consciousness. Nevertheless, hydropower-derived renewable energy has been fundamental to Nigeria's grid electricity generation since the 1960s. Until recently, the Kanji and Jebba Dams (1300MW) constituted around 50 percent of Nigeria's reliable power sources, having since been surpassed by gas power stations, whose functionality is limited by the deteriorating national system and inconsistent gas supply.

Power supplies in Nigeria are severely constrained: grid energy is accessible to just approximately 50 percent of the population, and even then, it is inconsistent. This has been essential to the initial growth of renewable energy in Nigeria. It has created a significant motivation to seek a more reliable solution that does not incur the continuous financial burden linked to the elevated expenses of electricity from the 'stand-by' generators, which have become the primary power source for numerous essential rural services.

The people and authorities in Nigeria have a limited understanding of wind and solar energy. The achievements are significantly less recognised than the deficiencies, which have been conspicuously evident in the unsuccessful solar street-light initiatives scattered throughout Nigeria's major urban areas. In popular perception, solar power plants have predominantly been synonymous with numerous unsuccessful government initiatives—evidence of inadequately implemented technology linked to favouritism and corruption.

Nevertheless, the achievements of renewable energy in Nigeria should prompt reflection among its detractors. The modest yet expanding array of solar energy initiatives that have been diligently executed have provided significantly improved service stability than analogous interventions. They also provide the most elusive benefits in rural Nigeria—feasible long-term sustainability. Global advances and enhancements in affordability regarding vaccine storage, rural water supply, and illumination for low-income populations are advancing rapidly and can be adopted for Nigeria.

Renewable energy must not be regarded in isolation. Advancements in the subject are intrinsically linked to enhanced energy efficiency, which has been essential in reducing costs and enabling new applications. In comparison to the current expenses of electricity in Nigeria, predominantly from generators, there is a compelling argument for significant interventions. This contrasts with other developing nations that possess a steadier grid electrical supply.

This article aims to investigate the well-known yet inadequately comprehended domains of solar power and energy efficiency, together with their consequences and prospects for Nigeria. It pertains to the power sector, emphasising some deficiencies in the proposed quick privatisation, along with the related hazards for individuals in rural areas and those with low incomes.

The coverage of wind, hydro, and biomass energy in this article is minimal—not because to a lack of promise, but because additional research is required before they can be effectively evaluated for Nigeria. The brief discourse on energy policy and the recent scenario analysis conducted by a World Bank team underscores the unexpectedly robust potential for low-carbon energy expansion in Nigeria. This pertains to the possibility for extensive growth of renewable energy, especially in northern Nigeria.

8. SPECIALISED APPLICATIONS FOR RURAL NIGERIA

Since the 1990s, numerous investigations on renewable energy in Nigeria have predominantly focused on photovoltaic (PV) solar power. This section highlights four applications of solar electricity that serve as models, demonstrating essential lessons on how renewable technology can be optimally tailored to local requirements. The models created are the culmination of years of incremental enhancements by many organisations or collaborations, leveraging both experience

and emerging technology. Due to spatial constraints, only a fraction of the evolution can be adequately represented here, and it is crucial to acknowledge the contributions of innovators—both socially progressive enterprises and NGOs—that have consistently endeavoured to showcase these new technologies in authentic rural settings.

8.1 Solar Water Pumping:

The availability of potable water has been a persistent issue in Nigeria, with many areas depending on water extracted from privately owned boreholes or those funded or established by the government. In each instance, there has been continuous instability due to the expenses associated with operating boreholes when grid electricity is either inconsistent or completely unavailable. Boreholes in rural regions typically depend on generators, which are costly to maintain and operate. Failures in water supply within relatively Brief time intervals are prevalent in numerous regions of the country, especially the Niger Delta.

The Niger Delta Wetlands Centre (NDWC) has been doing experiments with solar-powered water boreholes since the mid-1990s. A primary motivation is to directly contest the region's reputation for being 'too overcast' for efficient solar power use. The Centre has successfully showcased model water boreholes based on various fundamental concepts and has provided concrete proof refuting the "too cloudy" argument.

The architecture of the NDWC borehole water supplies is predicated on simplicity throughout all phases. Numerous solar systems include a combination of panels, charge controllers, batteries, and inverters to gather, store, and utilise solar-generated electricity. Each important component has specific maintenance requirements and susceptibility to failure. This presents a considerable difficulty in an environment characterised by inadequate planning and resources for maintenance, coupled with a limited understanding of emerging technologies such as solar power.

The NDWC solution aimed to reconcile conflicting challenges to achieve a design that was both straightforward and resilient. By selecting a system capable of delivering adequate drinking water during daylight hours, they chose a direct current (DC) system that obviated the necessity for batteries and inverters. This promptly eliminated two components that were the most costly and most susceptible to failure. The system compensates by monitoring anticipated overall water consumption, adjusting tank and daytime pumping and storage capacity accordingly.

The system possesses several well-established strengths:

- a) Investment in high-quality components yields exceptional durability.
 - b) Maintenance expenses are sufficiently cheap to be feasible in rural regions.
 - c) There is a persistent decline in the costs of key components, chiefly solar panels.
 - d) The efficiency of both pumps and panels persists in enhancing.
-
- a) Nonetheless, there are also significant difficulties that have been emphasised:
Low maintenance does not equate to maintenance-free; some professional assistance still necessary.
 - b) Preliminary capital expenditures remain considerably more than those of generator/grid systems.

- c) Alignment of capacity requirements with demand management—systems will operate solely within their storage capacity for a 24-hour duration and will not replenish overnight.

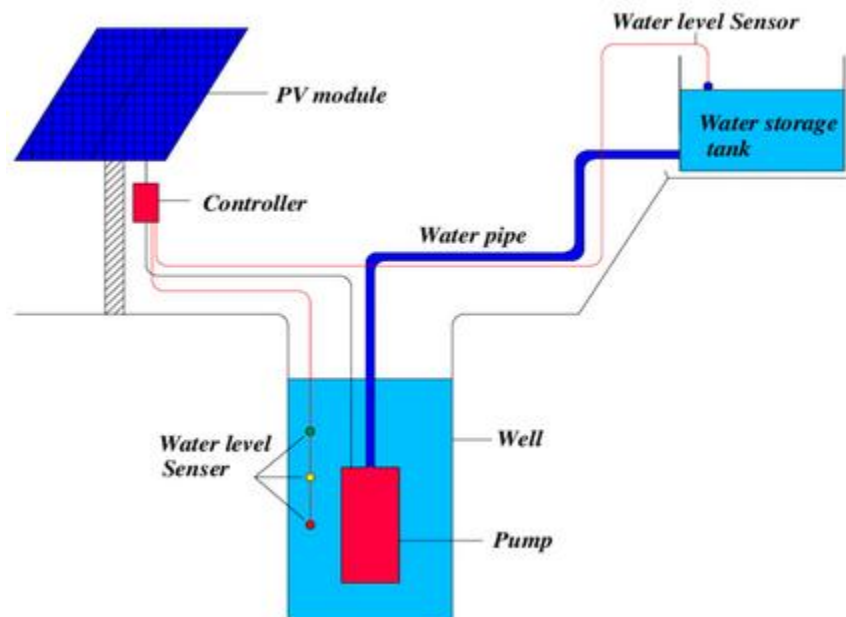


Figure 1. Basic elements of a direct current solar water-pumping system

The efficacy of this technology is well established in one of the least sunny regions of Nigeria; yet, some aspects require attention for the system to achieve its maximum potential. Following a phase marked by numerous unsuccessful installations, the Niger Delta Development Commission seems to have embraced the streamlined design initially advocated by NDWC as the regular procedure in rural locales. Nevertheless, some government agencies and departments persist in financing generator-based initiatives (notwithstanding their regularly elevated failure rate) or inadequately planned solar installations. There is less investigation into the 'right-sizing' of drinking-water supply designs to meet community requirements, with a preference for singular huge hubs irrespective of actual necessity.

Given the diminishing payback periods, wherein savings on fuel expenses completely offset the additional capital expenditure within 18 months to 3 years, it is evident that the technology need to be adopted as standard in 'off-grid' or inadequately serviced areas throughout Nigeria. This decision would also validate the modest investments required for research to enhance the alignment of system size with needs, as well as the comparatively low expense of regional technical assistance.

8.2 Small solar illumination devices

Similar to other solar uses, experiments in solar illumination in Nigeria have been conducted for some years, however they have achieved only minor success at best. The objective of the few projects observed by the author has been to offer illumination options to kerosene lanterns and small generators for homes with relatively low incomes. The initial systems utilised direct current

lights powered by diminutive solar panels, supplemented by batteries capable of supplying energy to minor devices like radios. They seem to have experienced the complete spectrum of obstacles faced by early solar trials in Nigeria: insufficient beneficiary engagement, difficulty in maintenance and supply chains, comparatively high short-term costs, and uncertainties over the ambitions of beneficiaries with diverse demands. Nigeria was not significantly exposed to the initial solar lanterns, which commenced at prices exceeding \$100 and exhibited performance considerably inferior to contemporary models.

Over the past three years, there has been a significant rise in lighting alternatives, cost-effectiveness, and dedication from developers targeting various regions of Africa, accompanied by noteworthy innovations within Nigeria. This is predicated on the advancement of economical and durable LED lighting accessories, improved battery alternatives, and significant reductions in the cost of solar panel components. The new devices are diminutive, with batteries and LED lifespans measured in years, with most batteries being 3–5-year lithium variants, and portable solar panels smaller than a shoebox.



Figure 2. Illustrations of small solar illumination systems.

The latest generation of products currently emerging in the market is rapidly establishing a comprehensive array of options for households and small enterprises—from economical kerosene lamp alternatives priced as low as \$15 retail to high-end systems that may cost up to \$500, providing enhanced illumination across multiple rooms while also charging laptops and mobile phones.

Targeting of design to specific prospective needs is developing. One concept, in collaboration with the Federal Ministry for the Environment, is primarily aimed at tiny hairdressing salons, which exhibit a clear minimal power requirement where designs can rival a small generator. The World Bank's 'Lighting Africa' program, which fosters the development of this new generation of products, has sought to tackle quality concerns by implementing a comprehensive quality assurance initiative that instills a significant level of consumer confidence regarding reliability. Section 3.1 of this paper provides a comprehensive analysis of technological advancements and their possibilities.

In Nigeria, solar illumination for families has transitioned from a marginal experiment plagued by substantial cost challenges to one with considerable potential. International initiatives fostering

collaboration and innovation have led to significant growth for small enterprises in various regions of Africa, alongside a nascent yet increasing recognition of the market potential and advantages in Nigeria.

The primary potential beneficiaries of this new generation of products in Nigeria are the substantial segment of the estimated 70 million Nigerians lacking access to grid electricity. The potential for dependable nighttime illumination for households and small enterprises, without a continuous financial burden, could be transformative for numerous individuals. The new items are experiencing a moderate introduction in Nigeria.

Despite significant advancements and substantial reductions in cost for household products, they nevertheless necessitate marketing, supply chains, product support, and alignment with customer capabilities and requirements. Various countries have implemented several different strategies to tackle these difficulties, ranging from microfinance to hire purchase schemes. These solutions are feasible in Nigeria, however they have frequently demonstrated greater challenges compared to other low-income nations.

If the current evaluations of these items are accurate—that they provide transformative improvements over their lifespan—then the constraints revert to financial considerations (refer to Section 6) and the establishment of a modest consumer industry. The significant simplification and cost reduction of solar lighting products may facilitate the emergence of modular combinations of small solar devices in Nigeria, allowing for customisation and upgrades based on needs, budget, and evolving household circumstances. Importantly, compact solar devices have attained a status as modest yet resilient assets that are reasonably portable and possess a considerable lifespan.

8.3 Refrigeration (vaccines and medical supplies)

Initial solar power uses in refrigeration fulfil a critical health requirement, similar to solar-powered water pumps. Nonetheless, both apps provide economical home alternatives as a primary objective for a significant majority of Nigerians. For several years in Nigeria, numerous companies have been implementing solar-powered vaccine refrigerators capable of providing consistent service in rural regions where resources for fuel and maintenance are typically inadequate. KXN Nigeria received an Ashden Innovation Award in 2008 for the deployment of solar-powered refrigerators in central and northern Nigeria.

Since its inception in 2002, the company has reported the installation of 767 refrigeration units at health institutions pivotal to the campaign against polio eradication. The refrigerators were tiny and utilised merely 60 watts of electricity due to enhanced insulation. In 2009, KXN approximated the costs per system, encompassing solar and refrigeration, to be approximately \$11,000. This encompassed expenses for a specialised firm functioning in a secluded region. A comparable rural generator-based system would have incurred a minimum cost of \$2500–3000, while the long-term fuel expenses would be exorbitant to maintain the requisite stable temperatures for storage. The expense associated with system failure, or depleting fuel, reaching as much as \$5400 for an entire batch of medicine housed in a single refrigerator, underscores the significant motivation for a reliable power source.

Interviews with other consultants revealed successful implementations of regional maintenance contracts, when a service provider managed a designated area encompassing many states for any

arising faults. This was coupled with training on-site personnel to manage fundamental issues and was considered highly successful at the time. The burden on service providers was minimal due to the excellent reliability of systems and the ease of resolving fundamental issues via a remote help desk. However, cost was evidently a constraint confining this technology to a specialised use, necessitating a complete system of panels, batteries, and inverters.

Recently, a UK business, Surechill, has exhibited significant advancements in integrating enhanced design and efficiency. The product is a refrigerator capable of enduring temperatures of 43°C for seven days without any power source, requiring merely a 350W solar panel array (slightly more than two standard panels) for fully off-grid functionality. Similar to advancements in other sectors, the efficiency improvements in this context significantly diminish the requirement for battery and inverter components. As a result, this has led to a significant reduction in total expenses. Even at introductory costs, Surechill solar units are projected to be approximately one-third the cost of previously installed systems.

Similar to the instance of IT centres (Section 2.4), the efficiency improvements in solar-powered refrigeration prompt the inquiry of whether numerous advantages could be attained with a smaller petrol or diesel generator. The inclusion of a reliable, well-maintained generator would reduce short-term expenses; however, the capital investment necessary for a solar alternative has significantly decreased to a more manageable level. Solar alternatives would incur higher initial costs; however, they would prove more economical over time in comparison to a generator. A solar system necessitates significantly lower expenditures than in previous years; yet, the reliability and little daily inputs needed for a high-quality system continue to be advantageous for solar electricity.

Solar energy remains a significant contributor to the reliability of refrigeration and supply networks for vaccinations. Interviews with solar practitioners and health organisations reveal lessons that seem to have been overlooked over time. The failure rate of refrigeration systems is considerable, accompanied by ongoing maintenance concerns. Some issues serve as reminders that solar systems are not the sole components necessitating maintenance, as fundamental refrigerator upkeep and replacement are evident concerns. However, instances of solar component failures due to trivial factors (such as dust or foliage on panels) exist, and prior regional support systems have not been sustained. There is a clear necessity to integrate insights from previous years and to leverage emerging technology.

Innovations in technology and fundamental enhancements outside the solar sector—such as more efficient commercially accessible refrigerators and freezers—indicate a need for a comprehensive reevaluation. Several years ago, refrigeration for middle-income households was considered excessively costly. With the advent of accessible freezers providing a fundamental 'remain cold' capability for several days, it is imperative to reassess and elucidate the potential of tiny home-solar systems to the public. The breakthroughs achieved by organisations at the forefront of inventive design indicate that even greater benefits are likely to emerge within the relatively brief periods typical of progress in renewable technology.

8.4 Off-grid IT Centres

The IT sector exemplifies the advancements in alternatives for systems powered by renewable energy. A persistent aspiration exists to enhance access to information technology and the internet for Nigerians, especially for individuals with limited incomes residing in rural regions. The anticipated advancements in social inclusion, education, information access, and governance are regarded as crucial for mitigating inequality disparities in Nigeria.

Nonetheless, the challenges associated with sustaining IT centres, especially in rural regions, closely resemble those encountered in other minor rural infrastructure initiatives, exacerbated by the delicate nature of the technology. The expenses associated with generating power, equipment maintenance, damage from power surges, and general deterioration have resulted in a significantly elevated failure rate over a little duration. In 2006, an NGO managing the STAND governance project in the Niger Delta explored an off-grid solar solution utilising standard personal computers, but the estimated cost was exorbitant—approximately \$120,000 for energising a rather modest centre.

Three years later, the succeeding project manager, SDN, who took over the project, chose to implement a pilot utilising newly built low-energy computers specifically engineered for challenging rural environments. Aleutia PC systems have diminished the energy consumption of a base unit to approximately 9W, down from 200–300W in 2006, while flat-screen displays have more than half their energy usage. Despite the absence of recent reductions in solar-panel prices, the expenses for a comprehensive centre decreased by more than 75 percent to below \$25,000, while the durability of the computers permitted a five-year warranty.

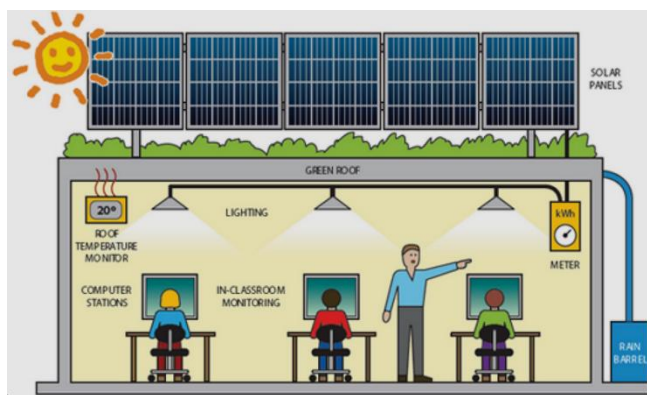


Figure 3: The Computer Classroom System

Numerous IT centres employing identical technology exist in various regions of the Niger Delta, along with a limited number of pilot projects in other areas of the country. The capital and energy requirements of systems have decreased, enabling the installation of stand-alone systems centred on a single modest solar panel. However, similar to other domains of solar technology, broader adoption has been constrained.

The potential of solar combinations in information technology appears more unequivocal than in other domains. Ongoing improvements in computing efficiency indicate that meticulously built IT

centres and classrooms could operate on minimal solar installations. Meticulous hardware selection may result in less maintenance and potentially decrease the required components. Schools have the opportunity to incorporate this into a good educational exercise regarding energy consumption and renewable resources.

Numerous states and agencies are allocating substantial funds to establish IT centres for educational institutions in both urban and rural regions. These projects frequently experience premature failure due to insufficient initial contracting and inadequate upkeep. The integration of solid-state technology with solar energy provides solutions to numerous prevalent issues. Nonetheless, advancement will necessitate a degree of public-sector dedication to the technology and several ancillary measures. The ongoing advancement of solar lighting should encompass a comprehensive integration of efficient, durable, and cost-effective components to provide solutions of exceptional value. The comparison of efficiency for laptops and tablets is clear, as premium products are already accessible internationally. In Nigeria, there is a necessity for enhanced integration of resilient computing, cost-effective batteries, and precisely calibrated solar energy.

8.5 Insights from Initial Pilots

All pilots and initial experiences in Nigeria exhibit clear technical proficiency and unrealised potential. A considerable aspect of this is undoubtedly related to financing and market development; yet, it is important to emphasise the shared factors connecting various applications. These include:

- Polished design, prioritising streamlined combinations of securely shielded components that are, when feasible, durable and solid-state.
- Advancements in technology and solar efficiency persist in rendering solar items and systems increasingly economical and dependable.
- An economically viable maintenance capacity and fundamental training for end users are crucial for sustainable performance.
- The education of government and agency managers regarding development budgets is likely essential for market growth.
- Access to foreign applied technologies should be prioritised to expedite their adaptation for usage within Nigeria.

9. IS THERE A PROMISING FUTURE FOR RENEWABLE ENERGY IN NIGERIA?

Notwithstanding the sluggish inception of dependable renewable energy technologies in Nigeria, there exists cause for optimism regarding their potential. This section examines significantly varied tiers of the same technology, ranging from consumer-grade items to grid-scale generation. This section's examples aim to illustrate developments and reflect only a portion of the ongoing changes. Recent advancements indicate that the foundational aspects and array of renewable energy alternatives in Nigeria are far more robust than acknowledged by the majority of policymakers and the public, necessitating an urgent response to the challenges posed by market and financial constraints.

9.1 Technology for Consumer Products

The technological advancements outlined in the pilots and specialised project applications of Section 2 are occurring more widely and at an accelerated pace. The promotion of solar lanterns and domestic illumination for low-income individuals underscores the rapidity of development. In

2009, development agencies and niche enterprises actively marketed the technology with considerable excitement. The price of an individual lantern ranged from \$100 to \$500, making it challenging to rationalise for low-income families.

In just three years, by 2012, the technology has solidified around significantly reduced costs, nearly indestructible LED lights, and battery longevity that can authentically be asserted to be between 3–5 years, with ongoing enhancements. The price of entry-level products is currently approximately \$25, and the payback period for the capital expenses of these products, in comparison to the daily expenditure on kerosene lanterns, is now credibly said to be significantly less than one year, thereby rendering a variety of new financing alternatives viable.



Figure 4. Low-cost solar-powered illumination Devices

Observations: LED lights have prolonged longevity and enhanced durability. Lithium batteries: offering warranties of up to five years.

The significant advancements in lighting stem from innovations in various facets of the final product:

- enhanced quality and cost of solar panels
- complete transformation in illumination technology
- novel generations of cost-effective lithium batteries
- removal of components—where independent systems can operate straight from batteries without inverters or replacement lights.

Moreover, a significant alteration in the market has occurred—the introduction of diverse competitive items with varied power levels, offering households a selection. Households utilising rudimentary kerosene lanterns undoubtedly experienced a lighting deficiency, rendering them unable of performing essential duties. The latest generation of solar illumination devices provides substantial enhancements over kerosene lanterns, as well as compact stand-alone systems appropriate for permanent installation in small residences. In the capacity of products As markets enhance, we can anticipate additional advancements in aligning inexpensive lighting solutions with genuine requirements.

Significant advancements in price are being achieved by removing supplementary requirements—expensive and energy-intensive inverters are unnecessary, and recent batteries exhibit enhanced

reliability and portability. The concurrent enhancement of lighting product efficiency and solar energy has significantly increased product accessibility. The prospect of addressing additional needs in a comparable manner seems to be expanding. There are enhancements in the efficiency of a substantial array of products utilised in households and small-scale services, with electronic products exhibiting notably robust and constant advances in efficiency.

Most households and small companies in Nigeria currently rely on small computers, LED televisions, radios, and lighting powered by petrol or diesel generators. Petrol generators incur expenditures exceeding 50 cents per kWh, far surpassing the expenses associated with unsubsidised solar power throughout its lifespan.

9.2 Extensive Generation Potential of Solar Thermal Energy

Nigeria's considerable oil and gas reserves, along with extensive coal deposits, have resulted in less consideration for renewable energy possibilities in power generation. All pilots mentioned have concentrated on independent designs, with merely a few isolated efforts to investigate village-sized installations. Figure 3.2, depicting the global intensity of solar radiation, was utilised by Lumina Decision Systems in a framework for solar thermal power in Nigeria for a World Bank research. It positions Nigeria comparably to Spain, the foremost developer of solar thermal power outside the United States. The southern and eastern regions of Nigeria see prolonged durations of substantial cloud cover, considerably diminishing solar radiation intensity. This does not imply that solar electricity is unfeasible in southern Nigeria. Solar power involves generally high-energy procedures and requirements, utilising mirrors and light concentration, however solar PV panels can endure a broader spectrum of daily conditions and have been effectively shown in southern Nigeria.

Solar thermal power exemplifies an emerging renewable energy technology characterised by a brief history yet accompanied by significant confidence on its trajectory and eventual potential. In a little period, it has addressed two significant challenges: substantially reducing generation costs and creating effective energy storage capable of providing electricity overnight. Solar energy derived from photovoltaic panels has the inherent limitation of generating power solely during daylight hours, while nighttime reliance is confined to the comparatively costly alternative of batteries.

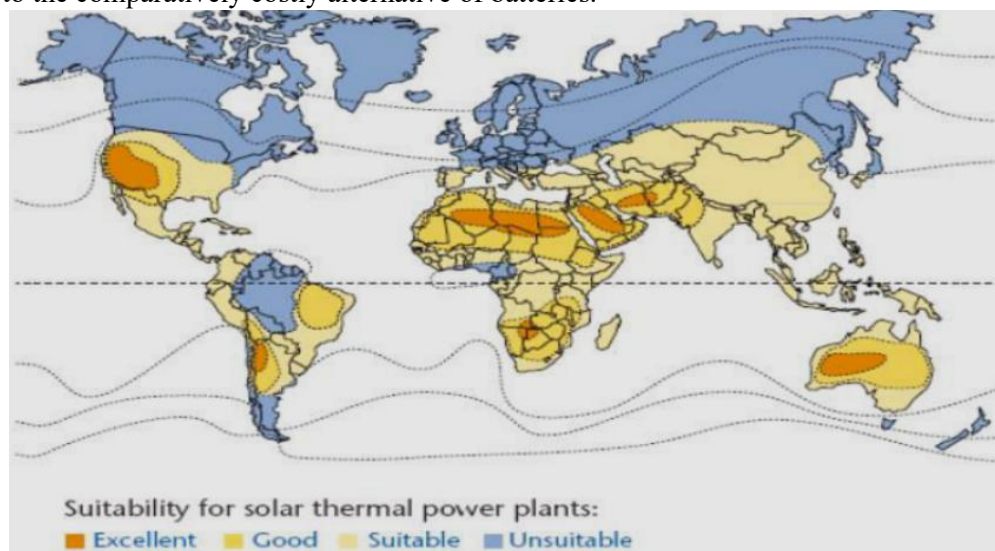


Figure 5. Worldwide prospects for solar thermal power facilities

(https://www.researchgate.net/publication/311695640_Forecasting_transition_electricity_solar_energy_from_Mena_to_Europe/figures?lo=1)

Thermal solar utilises highly heated salts to serve as an energy source for the turbines that generate consistent and continuous power throughout the day. The technology is sufficiently nascent that its pricing is still determined by few data points and an anticipated decline in expenses. The confidence in the technology has already resulted in the remarkable Desertec project in the Sahara Desert. European enterprises have ample confidence in price patterns, enabling them to strategise for a substantial installation throughout northern Africa, facilitating high-voltage power transmission to Europe. Initial investments above \$1.5 billion have been secured in Morocco, with the expenses associated with next-generation transmission deemed 'small' supplementary charges.

The World Bank's analysis of Nigeria estimated that designating 5 percent of eligible land in central and northern Nigeria for solar thermal might yield a theoretical power production capacity of 42,700 MW. In actuality, the global installed capacity of this technology is now below 20,000 MW.

The primary obstacle hindering widespread adoption of this technology is cost; nonetheless, advancements have been as impressive as those seen in other leading solar technologies. In 2004, pilot plants incurred costs of approximately \$0.45 per kWh, whereas third-generation systems, developed a few years later, cost between \$0.17 and \$0.20 per kWh. While not yet competitive with the efficient installation of gas or coal (see to Section 6), this cost is significantly lower than what most Nigerian households and businesses incur when relying primarily on household generators. Northern Nigeria and the Middle Belt are evidently situated atop a substantial energy reserve, which is rapidly becoming economically feasible. Considering that these regions present a more costly and complex electricity distribution from southern Nigeria, there is a compelling argument for a thorough investigation of the region's energy potential. The case for this is further bolstered by the extensive geographical distribution of solar thermal potential. In several instances, it ought to be feasible to envision low transmission lengths and comparatively rapid building in contrast to gas plants that depend on extensive pipes or protracted transmission networks.

A cautionary note: the expected competitiveness of solar thermal plants relies on medium to large-scale installations. The projected cost-efficiency improvements are predicted to reach up to 50 percent, scaling from modest pilot projects to cumulative installations of approximately 5000 MW. This does not diminish its total potential; however, it underscores the necessity for readiness to see the technology as a significant capital expenditure.

9.3 Alternative Renewable Energy Sources

Beyond the well-known solar photovoltaic technology, other renewable energy sources garner less consideration or focus. Hydropower, Nigeria's most substantial renewable energy source by current capacity, has served as the foundation of grid-based electricity generation for decades. Currently, analysts may identify notable hydropower sources and proposals, like the dam for the Mambilla plateau in eastern Nigeria; however, substantial investments and extended timelines have engendered scepticism regarding their advancement.

The most substantial change anticipated in the short to medium term regarding hydropower is the pressing necessity to revamp current hydro-generation systems. Current turbines are significantly outdated and generating only over 50 percent of their capacity. The most poorly comprehended source of renewable energy in Nigeria appears to be wind power. Until recently, Nigeria was

perceived by both domestic and foreign policymakers as 'not a windy country,' a conclusion derived on a notably restricted dataset. There has been a notable scarcity of available data to either substantiate or refute this claim.

In 2005, Lahmeyer International evaluated wind velocities at 10 sites in Nigeria, determining average wind speeds of 4–5 meters per second at a height of 30 meters (suggesting 5–6 m/s at 80 meters). These modest speeds can indeed warrant installations in sites near the upper limit of this range, particularly in areas with the most stable conditions. The seeming disinterest in wind power appears to arise from the failure of these statistics to reflect the substantial resources available in certain 'windier' nations. The potential for wind energy in Nigeria is evidently less significant than the substantial potential projected for solar thermal energy.

Considering the enhanced price-competitiveness of wind power, the advancement of specialised applications at moderate wind speeds, and the relative simplicity of its modular deployment, wind power warrants increased research and pilot implementation in Nigeria. Comprehensive mapping would elucidate its potential for rural regions, especially when integrated with other power sources. Mapping in countries like the UK illustrates the degree of variance that emerges when generalised figures are replaced with unique local data. Although large-scale generation may be confined to select sites, the 'off-grid' potential of wind power in remote regions, especially the coastal Niger Delta, remains largely unexamined.

A substantial wind pilot project of 30MW is being established in Kano State, alongside a further pilot project in Katsina State. These may offer the inaugural locally accessible proof of the operational dynamics of grid-level wind power under local conditions for Nigerian policymakers and the public regarding the prospective role of wind energy. However, the implementation of smaller initiatives for off-grid rural communities should be prioritised. Frequently overlooked in extensive mapping initiatives, the creation of combinations could mitigate seasonal variations and other limitations. The most effective globally is the combination of wind power and diesel generating for periods of low wind speeds. The widespread presence of substantial 'community' diesel generators in the Niger Delta presents a clear opportunity to explore alternatives to the prevailing situation, where fuel supply issues frequently result in intermittent rather than dependable electricity provision from these generators. Solar and wind energy may be a viable combination for the same populations, as their seasonal strengths mitigate each other's limitations.

9.4 Investigating Uncharted Territory

The previous two decades of cautiously researching renewable energy in Nigeria underscore the importance of maintaining an open mindset towards advancements in new and enhanced technology. The fossil fuel industry in Nigeria is nearing its fiftieth anniversary, whereas renewable energy sources, aside from hydro, have just recently begun to get attention in the past decade.

Section 6 will examine the declining cost of renewable energy, as advancements in technology become increasingly accessible and efficient. However, it is not solely the expense of generating that is propelling new opportunities. This section will examine a significant development associated with renewable energy: advancements in energy efficiency across many equipment, including computers and air conditioners. The preceding sections have examined the possibility of

specialised renewable energy uses and large-scale generation; nonetheless, the predominant energy consumption occurs within Nigeria's 'mass household market' with its 160 million inhabitants. Given the diverse requirements, a comprehensive analysis of Nigeria's domestic energy consumption is unfeasible; however, it is pertinent to underscore many critical issues that warrant exploration in the context of renewable energy.

The consumer-grade products discussed in Section 3 suggest potential trajectories for economical mass-market offerings. This trajectory will be shaped by some technological advancements already noted, as well as the essential and continuously evolving backdrop of generation and demand elaborated upon below.

10. ENERGY REQUIREMENTS AND ASPIRATIONS

There is less unanimity regarding household-level demand and energy requirements in Nigeria; however, it is generally acknowledged that the magnitude of the issue is significant. For an illustration of the extent of disparity, one need merely examine estimates of decreased demand for grid electricity. Assuming an endpoint of approximately 1KW consumption per capita, similar to that observed in most affluent nations, Nigeria's theoretical demand for electricity would be approximately 160,000MW, in stark contrast to the relatively minimal generation of under 5000MW currently produced.

The challenge of aligning demand with supply, prior to considering industrial requirements, seems daunting and distant from the 'stable electricity supply' assured by political figures for the forthcoming years. Lai Yahaya's future article addresses power generation concerns and strategies, whereas Figure 4.1 aims to depict the probable significant disparity between power demand and supply in Nigeria.

The estimates for electricity consumption and demand of 'off-grid' generators in Nigeria exhibit a remarkable variability. Official calculations estimate demand at 20,000 MW, however alternative assessments for a population over 160 million suggest far higher demand. Despite its robust industrial expansion, South Africa, with a population of 50 million, serves as a pertinent indicator, as its generation capacity of 40,000 MW barely satisfies demand. Figure 4.1 illustrates the persistent deficit if the 2007 demand was merely 40,000 MW, accompanied by a mere three percent yearly increase in power consumption. The disparity becomes far more pronounced when a starting point of 60,000 MW is regarded as a more precise estimate of demand.

Actual repressed demand is, undoubtedly, far more intricate than a singular headline calculation. A significant portion of Nigeria's population is unable to buy consumer items that would typically elevate energy usage to Western standards or higher. They would also likely struggle to bear the expense of the overall rise in energy usage. This has resulted in estimates of repressed energy demand ranging from 20,000MW to 80,000MW, with all analyses dependent on alarmingly little data.

Two inferences can be drawn at the household level from the limited data. The energy supply deficit for the bulk of the population will persist significantly for the next decade and beyond. The actual expense of electricity will continue to reflect the prices associated with commercial and residential generators, which start at \$0.50 per kWh and increase from there. Reforms in the power

industry will be crucial for economic growth stemming from increased grid energy output; nonetheless, power supply will be insufficient, leaving many regions essentially excluded or subjected to significant rationing.

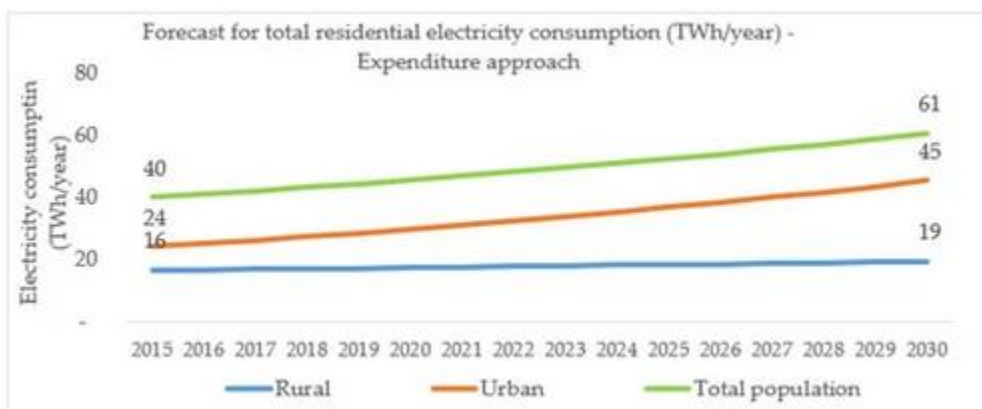


Figure 6. Projected electricity consumption in Nigeria Source: <https://www.mdpi.com/2071-1050/10/5/1440>

In the setting of power rationing and exploring other energy sources, Nigerian families would persist in prioritising a combination of affordability and accessibility. The issue of affordability will ultimately be influenced by circumstances largely outside the control of most users, chiefly the dependability of the power supply in their region.

10.1 Decentralised Renewable Energy (DRE)

The most efficient and pragmatic approach to enhance electricity access and diminish reliance on diesel generators is through decentralised renewable energy solutions. These encompass solar home systems (SHS), community-oriented mini-grids, and specialised installations for essential institutions such as educational facilities and healthcare centres. Decentralised renewable energy sources mitigate significant transmission losses and can be swiftly implemented in areas where grid expansion is sluggish or economically impractical. Ongoing initiatives spearheaded by the Rural Electrification Agency (REA), in collaboration with international development partners and financiers, are expanding mini-grids and advocating for energy-efficient productive-use appliances, thereby establishing reliable power access and fostering new avenues for local economic development (NCCC, 2023; ETP, 2023).

This report delineates three fundamental categories of energy consumers who may contemplate transitioning entirely or predominantly to solar power.

1. Households and enterprises outside the electrical grid. In rural locations lacking the promise of dependable grid electricity within around three years, consumers have a singular source of competition for renewable energy: petrol and diesel generators. Given cost structures of \$0.5/kWh or significantly more for generators, renewable energy can be instantly competitive despite substantial initial capital expenditures.
2. Individuals situated at the periphery of the grid. Although there is a scarcity of genuinely dependable statistics, it is evident that for a significant portion of the country, access to the grid entails an erratic supply of electricity, fluctuating between a few hours weekly to four hours daily. A significant portion of the population belongs to this group. Renewable energy remains competitive for this cohort due to the limited and inconsistent nature of grid supply.

There exists the potential for 'optional' high-energy-demand chores to be deferred to grid electricity, so considerably diminishing the size of the solar system required to meet other demands.

3. Those are 'just partially obscured.' In places like Lagos and Abuja, certain areas can anticipate 8–12 hours of electricity daily with relative consistency, in contrast to the remainder of the country. This group is expected to profit from an efficient inverter and battery backup system, which would utilise the lower cost of grid electricity while offering significantly superior and more economical alternatives to a generator during grid outages.

Table 1. Variations in Energy Efficiency for Domestic Products in Nigeria

Power consumption (watts)			
Product	2002	2012	Maximum efficiency (for a solar installation)
Lighting	600 (6 bulbs, 100W each)	120 (CFL bulbs)	80 (LED lighting]
Television	300	50 (flatscreen)	20 (LED flatscreen)
Fridge	500	300	150 or lower (energy-efficient versions)
Fans	150 (3@50W each)	150	120
Total	1550	620	370

10.2 Domestic Decisions, Energy Efficiency, and Renewable Resources.

Household decisions on consumer products to satisfy their demands will significantly impact energy demand in Nigeria and the significance of renewable energy. One of the primary obstacles to the broader adoption of solar electricity in nations such as Nigeria is the substantial initial capital expenditure. Evidence from specialist pilot applications indicates that selecting more efficient goods to fulfil requirements will significantly affect the overall system cost.

At the consumer level, savings achieved through energy efficiency or prioritising low-energy needs influence every aspect of a solar power system: fewer panels are necessary, a smaller inverter suffices, and the quantity of batteries is significantly diminished. Consequently, it is evident that advancements in energy efficiency over the past decade have significantly enhanced the likelihood of modest solar installations fulfilling household requirements. Table 4.12 delineates modifications that are comparatively attainable in Nigerian markets.

Moderate-income households utilising appliances depicted in Table 4.1 have experienced a reduction in energy requirements by over two-thirds when employing contemporary iterations of commonly used consumer products. The increases are inconsistent; nonetheless, in many instances, advancements in areas such as computers and lighting have prompted forecasts of significant progress occurring nearly as rapidly as the standard in computing power.

The author derives energy use figures from 'average' commercially accessible products in Nigeria. 3 Regarding the advancements in the efficiency of computer products, many of which are currently propelling the revolution in smartphones and mobile computing, refer to <http://www.extremetech.com/>

computing/95913-koomeys-law-replacing-moores-focus-on-efficiency-with-power.

The concluding column of Table 4.1 denotes the reductions achievable with supplementary investment, despite the persistent challenges in Nigeria where options remain severely constrained. The aforementioned choices do not address the intermittent demand from high-consumption equipment like irons, kettles, and water heaters, although they significantly underscore the potential reduction in energy requirements to satisfy essential daily needs.

The table also emphasises two additional concerns: the necessity for consumers to understand their energy alternatives and the significance of cost-effective 'high-efficiency' technologies. In the absence of more efficient products tailored to local requirements, these benefits may remain theoretical for numerous households and small enterprises. The accessibility of more efficient products is essential for consumers contemplating the possibility of using solar energy.

10.3 Consumer Education, Choices, and Supply Chains

A distinct opportunity for renewable energy exists at the household level in several regions of Nigeria. Significant declines in solar power prices and energy demands create a formidable synergy to rival generators. However, these are merely two essential components of the more intricate puzzle of consumer decisions.

Essentially, substantial progress towards renewable alternatives will not occur until there are evident and accessible solutions that address household need. Disregarding initial expenditures, the market features a limited number of dealers for domestic solar systems, and their reliability is markedly inconsistent. Although the availability of energy-efficient items has improved somewhat, consumer and distributor awareness regarding the energy worth of these products remains low or frequently absent.

A straightforward 'catch-22' predicament seems to be in operation. The capital expenses associated with solar systems are hindering the advancement of supply chains for solar and efficient products, limiting consumer options for inexpensive combinations that meet their requirements. However, enhanced supply chains, consumer education, and access to the newest cost-effective innovations will provide a further reduction in costs, potentially stimulating substantial demand. Policymakers, suppliers, funders, and investors evidently share a mutual interest in resolving this 'catch-22' predicament. Their duty is exacerbated by the current circumstances. The subsequent section of this article delineates a severely impaired market for renewable energy goods. However, the fundamental trajectory becomes distinctly evident—technology has evolved and been substantially validated. The remaining tasks include market research, further adaption, and product combination to align with the requirements of a highly diversified community.

10.4 Is the market fractured?

Given the advancements in niche solar uses and the swift improvement in energy efficiency and cost reduction, one may anticipate a rapid expansion of Nigeria's renewable energy business. The Nigerian solar business is characterised by sporadic instances of success overshadowed by several government-sponsored projects that exhibit an exceptionally high failure rate. Rather than a vigorous market gaining assurance, there exists an emerging sector impeded by a reputation that has significantly deteriorated over the last five years, especially in southern Nigeria.

Moreover, there exists a significant hesitance among individual users to invest in renewable energy systems (or even inverter-battery backup systems) due to the substantial initial expenditure. This interacts with a deficiency of accessible evidence for average consumers regarding the likelihood of their investment's success. Identifying trustworthy vendors and installers for solar equipment, together with substantiation of successful models, is challenging and labour-intensive. The situation is exacerbated by the frequent lack of dependable warranties or service providers capable of delivering both high-quality equipment and maintenance. This section examines the primary causes of a decline in market confidence and potential treatments.

10.5 Patronage Contracting

The substantial capital investment required for solar projects has rendered them appealing to government entities that favour large-scale initiatives and invest with minimal understanding of necessary objectives, contractors, and technical fundamentals. This seeming disregard and absence of accountability appear to be only an extension of the patronage contracting issue, where the interests of administrators and contractors are focused on maximising profit.

Project completion and short-term sustainability seem to be variable criteria, where the extent of permissible actions significantly impacts implementation more than adherence to best practices. Regrettably, this issue is not exclusive to solar energy. This phenomenon in development contracting occurs when numerous key stakeholders prioritise patronage and dubious contractual prospects over the ultimate outcome.

Examples that are recognised include:

- The Niger Delta Development Commission has commissioned numerous major solar water projects, each above \$300,000, since 2006. Concise surveys indicate that the overwhelming majority of this initial phase of initiatives were either never finalised or failed shortly after implementation.
- Projects pertaining to the Millennium Development Goals. This presidential agency either contracts development projects or collaborates with states. Reviewers have raised concerns that most projects seem to fail shortly after initiation, with inadequate implementation and maintenance being the predominant issues. These deficiencies are not exclusive to large federal government agencies but are also evident in various extensive state initiatives in Nigeria. Nasarawa State commissioned 147 solar water projects in 2004, aiming to offer one for each ward within the local governments of the state, according to an interview with an unnamed consultant due to the ongoing review status. A evaluation conducted by Iceberg Consulting, commissioned by the state government, revealed that 83 percent had not succeeded. The causes of failure are akin to those that the reader will encounter repeatedly throughout this report:
 - Ineffective technical system design and installation
 - Improper acquisition of borehole and solar array installation
 - minimal or no training provided to the end users within the community
 - insufficient upkeep.

The prevalence of substandard work executed via patronage contracting persists, accompanied by few reactions to evident issues. Similar to other development initiatives in Nigeria, there is a lack of effective oversight over service delivery and accountability for sponsors of numerous unsuccessful projects.

The impairment of the impression of renewable energy, both in governmental circles and among the populace, is considerable. An escalating number of towns have had failures in solar projects, likely surpassing those with favourable experiences where their systems continue to operate effectively after several years.

10.6 Challenges Associated with Solar Street Lighting

Solar street lighting initiatives have adversely impacted the views of renewable energy in Nigeria more than any other deficiency within the nascent industry. Since around 2003, they gained popularity among state governments as a rapid solution for inadequate lighting in urban areas resulting from unreliable grid electricity. Nevertheless, the installed systems generally employed inexpensive and inadequately integrated components, miscalculated battery demand, and experienced substandard installation and insufficient maintenance.

Many designs observed in Nigeria use batteries placed within a metal enclosure on the streetlight pole. In tropical regions, this can be a detrimental decision as battery longevity is typically significantly compromised by elevated temperatures. Numerous devices may have failed due to their batteries being overheated by the solar energy they were designed to store. Most state-installed systems are claimed to have malfunctioned within approximately six months. In Rivers State and Bayelsa, the majority of solar systems installed circa 2006 were dismantled and substituted with conventional lighting due to their failure within 12 to 18 months. In several states, malfunctioning solar street lights serve as a mute testament to improper solar installation practices.

Implementing effective solar street lights is tough yet feasible. The required illumination is at the higher limit of solar power capabilities without incurring prohibitive expenses, however this has significantly improved with the introduction of LED lighting. Two exceptional instances illustrating this in Nigeria are the lighting system at FERMA in Abuja and a supplementary system implemented by Iceberg Consulting in 2003 in Nasarawa State, which continues to operate eight years later.

10.7 Inconsistent quality across installers and vendors

The renewable energy marketplace appears weak in comparison to other regions with considerable grid deficiencies, such as Kenya. The extensive generator market developed over decades in Nigeria, catering to needs from under 1kVA to major hotels, underscores the substantial growth necessary for renewable energy to play a significant role in the country's overall energy mix.

Until recently, the limited renewable and solar vendors in major cities appeared to depend predominantly on contracts from government entities or oil firms for installations, which they frequently lack the qualifications to execute proficiently. Vendors frequently appear to be a blend of the inexperienced, possessing commendable yet occasionally naïve goals, or more cynical entities that exhibit minimal regard for their products, provided they can only pass an initial inspection and formal commissioning. High-quality installers and vendors exist, but they are infrequent and typically difficult to locate for individuals lacking established networks.

The feeble position is exacerbated by the hesitance of private individuals to invest the necessary capital for a modest home system or comparable alternatives. Two solar dealers interviewed by the author acknowledged that they had not installed solar systems in their residences due to the cost, despite residing in areas where grid electricity was frequently accessible for just 2–4 hours daily.

The difficulty for the public and prospective sponsors of renewable projects in locating competent, seasoned practitioners is significant. The cautious emergence of renewable energy in Nigeria has rendered individuals with 5–10 years of experience in the sector both scarce and somewhat isolated. Throughout the preparation of this paper, the author encountered well-meaning persons with the resources to invest in small solar installations, yet lacking knowledge on how to identify a good company to execute the operation.

In Nigeria, there exist just a few associations of solar or renewable energy practitioners, mostly affiliated with other organisations. The Ministry for the Environment's renewable energy program maintains a database of stakeholders; nonetheless, this does not mitigate the relative isolation of professionals in a diminutive business inside a vast country.

10.8 Instructional Insights and Market Remediation

The harm inflicted on the market by the proliferation of unsuccessful sponsored solar initiatives over the past decade, along with several dubious minor items, cannot be rectified swiftly or effortlessly. The significant harm to views indicates a clear focus area: prominently showcased 'best practice' projects designed to exemplify cutting-edge technology and alter public opinions.

The government plays a crucial role by providing venues and locations for installations that will be regularly observed. The government maintains a proficient central hub for its renewable energy initiatives at the Ministry of the Environment. It is realistic to anticipate that projects focused on enduring quality and attitude transformation could originate from this location.

Addressing market issues necessitates a meticulous integration of market intelligence, targeted consumer education, financial support for emerging industries, enhanced vendor visibility, and regulatory measures to foster market confidence. Such endeavours to establish 'an industry' might readily misfire or yield unforeseen repercussions. Consequently, it is imperative that these measures are meticulously formulated in conjunction with established practitioners.

The subsequent section of this article examines a crucial aspect of market development—financial requirements for a sector characterised by significant upfront capital expenditure. Addressing these concerns collectively as a cohesive approach will facilitate a definitive pathway towards a robust renewable energy market.

11. FUNDING RENEWABLE ENERGY INITIATIVES IN NIGERIA.

The funding of renewable energy initiatives is regarded by both professionals and analysts as the primary obstacle to the increased adoption of renewable energy. Even individuals closely associated with the tiny industry have refrained from implementing systems due to the substantial capital expenditure and the protracted 'payback' period in a challenging market. This part will address the emerging difficulties related to capital expenses and the resulting financing requirements for households.

11.1 Adjusting Capital Expenditures

The substantial capital expenditures of solar products have been identified as a significant obstacle to the adoption of this technology, regardless of consumers' economic levels. The disparity is considerable in both residential and commercial systems within a predominantly cash-based economy. This is applicable at all tiers within the market. A homeowner may be evaluating a solar

lamp priced at N3000, which requires no energy inputs, against a kerosene lantern costing N300, which necessitates ongoing fuel expenses. Another instance is the decision between investing N40,000 in a generator or N200,000 in a small solar/inverter system. The problem of securing initial finance for solar systems is significant in all instances.

For consumers to make a significant commitment to renewable sources, the benefits must be unequivocally evident. In many instances, this indicates that aligning a consumer's energy requirements with the most efficient renewable alternatives is essential for securing both acceptance and substantial benefits.

11.2 The Mitigation of Core Costs in Solar Photovoltaics

Currently, with a little market and very minimal revenue, it appears improbable that the reductions in the cost of solar PV electricity have entirely permeated Nigeria. It appears improbable that these expenses have been entirely incorporated into the calculations conducted by suppliers and installers of solar systems.

Nonetheless, the decline in prices has intensified during the last four years. Although there is a degree of variability in the optimism reflected in Figures 7 and 8, the comparison of photovoltaic (PV) energy to alternative sources conveys a consistent message: the significant advancements in solar technology suggest that the issue is not whether, but when solar power will surpass existing fuels in competitiveness.

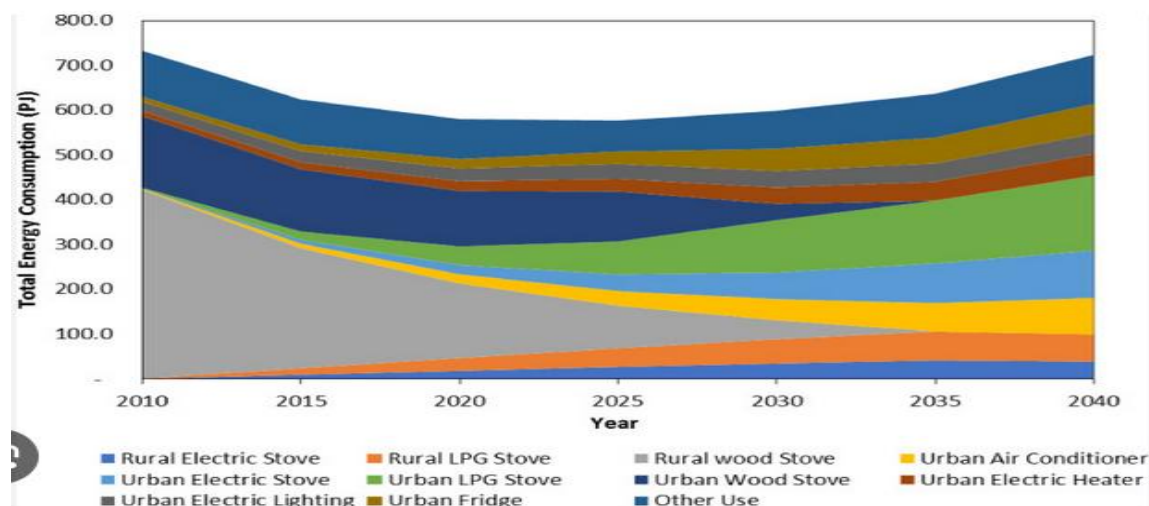


Figure 7. Forecasted cost of solar photovoltaic versus conventional, 2005–2035
Source: <https://www.pv-magazine.com/2025/06/18/nigeria-expected-to-hit-only-1-5-gw-of-solar-by-2035/>

Figures 7 and 8 both underscore two prevalent themes. The initial factor is the persistent decline in the fundamental costs of renewable energy. The effect of this at the home level may be exaggerated (see to Section 6.3), however the magnitude of the decline in costs remains favourable at both macro and micro levels. It has ramifications for business planning, even in the short term,

emphasising the necessity for installers to access superior current products and for their clients to be informed about options that incorporate the latest advancements.

Figure 8 exemplifies several estimates of electricity price trends; nonetheless, it is crucial to recognise that it consolidates 'average' costs rather than emphasising actual local situations. The elevated expenses associated with generation infrastructure projects in Nigeria suggest that conventional power costs are considerably higher, with a substantial dependence on gas for generation. Secondly, both figures juxtapose renewable energy with current grid power alternatives. Given the limited access to grid electricity in Nigeria, dependable grid power is not a feasible choice for the majority of Nigerians. Section 6.4 seeks to contextualise the contrast between renewable electricity and its primary realistic competitors among generators.

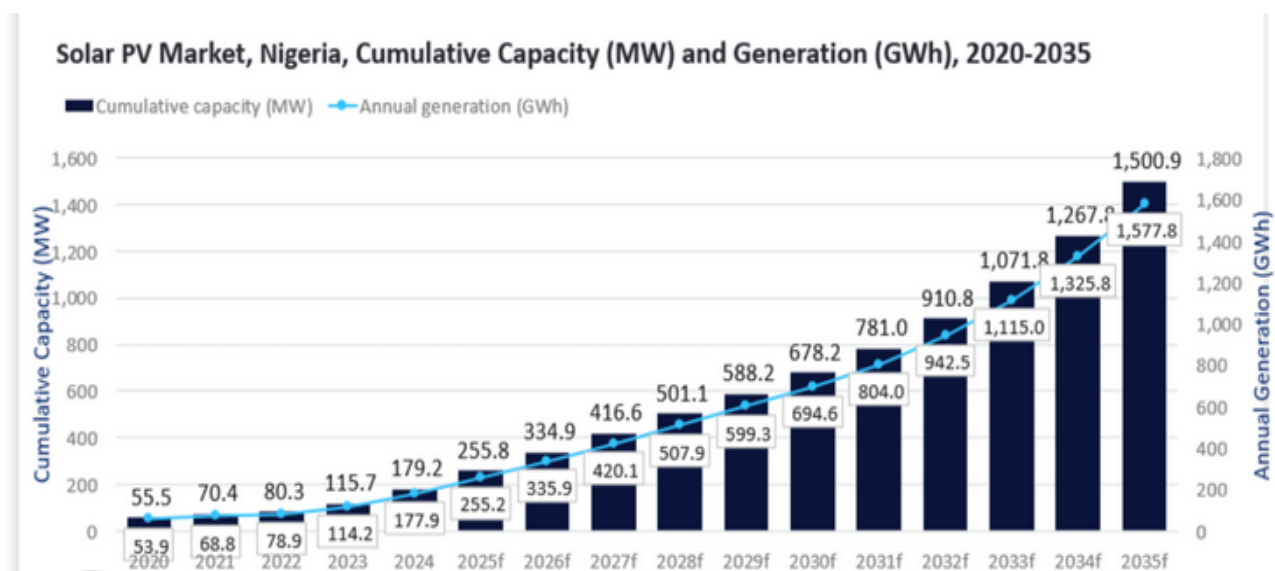


Figure 8. Anticipated expenses of various energy sources, 2010–2035

Source: <https://www.sciencedirect.com/science/article/abs/pii/S2666278721000428>.

11.3 Installation Expenses

In smaller projects, both in Europe and Africa, the decline in solar panel prices and diminished energy requirements have underscored a fundamental challenge. The installation cost of a system, rather than the theoretical efficiency of a panel, is the primary factor influencing cost and value. This renders labour costs and industry efficiency increasingly pertinent in assessing potential advantages for customers.

In Nigeria, the diminutive scale of the renewable sector seems poised to maintain elevated installation costs compared to other nations, at least in the short future. This also highlights another essential objective. Given that labour costs in Nigeria are lower than in many nations used for installation comparisons, it is essential to cultivate professionals capable of delivering competent and cost-effective services. The growing body of analysis emphasises that the majority of jobs related to renewable energy are to installation and maintenance, rather than the increasingly mechanised manufacturing sector.

Alongside cost and energy efficiency, quality is equally crucial for dependable components. Nigeria presents numerous dangers that might significantly impair equipment, rendering renewable energy capital investments considerably more costly if challenging repairs or replacements become necessary. Investing in supplementary protection against hazards such as lightning, accidental damage, or misuse has demonstrated significant benefit in experimental projects, and this approach is likely applicable to most consumer scenarios.

Ultimately, these expenses underscore the advantages of certain smaller 'product' solutions where they are suitable. High-quality solar lanterns or compact DC lighting systems do not necessitate specialised installation expertise and, when equipped with LED lights, exhibit remarkable durability against damage and misuse. Consequently, compact modular programs evidently possess a significant edge in capitalising on recent advancements.

11.4 The Competition: Generators and Kerosene

When evaluating the expenses associated with renewable energy, a significant consideration sometimes overlooked is the exorbitant amount that the majority of Nigerian consumers presently incur for lights and power. Surveys indicate that 50 percent of the population lacks access to grid electricity, while many others have limited access for only a few hours weekly; thus, the primary energy sources for a substantial segment of the population are derived from alternative means.

Acquiring comprehensive expenditure and cost assessments is difficult. The majority of customers limit their utilisation of generators, lanterns, and alternatives, while there is significant heterogeneity in the efficiency of the devices employed. Moreover, these calculations fail to consider the expenses associated with substandard fuel (which diminishes generator lifespan), fuel procurement, and erratic price fluctuations and shortages. A more thorough review of these expenses for the majority of consumers is likely to persuade them that a well-engineered solar system will reduce the operational costs of a generator or the daily expenditure on kerosene for lanterns.

Bermuda and other island nations exemplify the indicative costs for household consumers in isolated places dependent on diesel. This region is initiating a significant initiative for energy efficiency and enhanced utilisation of solar power, partially in response to grid electricity pricing of \$0.45/kWh. Individuals involved in rural initiatives may also reference detailed information from an extensive evaluation in Namibia, which monitored decreasing payback periods and performance metrics aligned with the experiences of NDWC in the Niger Delta. In both instances, data predating 2010 demonstrated that the duration required for larger capital expenditure in solar systems to yield net savings was less than three years and decreasing. Post this juncture, savings would signify a substantial benefit for communities and investors.

11.5 Feed-in Tariffs

Representatives from both NERC10 and the federal government of Nigeria have expressed their willingness, albeit without specifics, to establishing a renewable energy feed-in tariff aimed at fostering industry growth. In numerous nations with advanced renewable energy infrastructure, "feed-in tariffs" encompass compensation that residences and small enterprises can obtain for surplus power they generate and contribute to the electricity grid. Nonetheless, the majority of

analysts and stakeholders in the power sector have informally deemed this notion unworkable in Nigeria due to the precarious and disordered condition of the current system. This is likely accurate for small installations or families, but may not be readily dismissed for larger enterprises capable of sustaining substantial renewable energy.

If the federal government recognises the robust economic rationale for the development of renewable energy in the longer term, particularly in northern Nigeria, then the implementation of feed-in tariffs to incentivise sector growth should be meticulously evaluated. In Europe, where numerous technologies possess fewer inherent advantages, the feed-in benefits are considerable. The United Kingdom is currently decreasing its green feed-in tariff to a substantial 21 pence (52 Naira) per kWh, down from over 40 pence (104 Naira).

This rate may appear excessive in Nigeria, where analysts anticipate the gross tariff (prior to any temporary alleviation) to increase from the current 10 Naira to between 20 and 30 Naira per kWh. Conventional estimates of generator costs, approximately 70–80N (\$0.45–0.50), underscore the necessity of scrutinising the comprehensive context of cost-benefit evaluations. It is important to note that certain issues associated with renewable energy may be perceived as advantages within the framework of Nigeria's challenging power circumstances (Table 6.1).

Additional hazards exist within the framework of a feed-in tariff for Nigeria. Fuel subsidies have demonstrated to be detrimental avenues for contract exploitation and fraud. Any feed-in tariff must function with exceptional transparency within a demanding market environment. There is a compelling argument for using feed-in tariffs to accelerate the large-scale development of renewable energy in northern Nigeria. This could potentially facilitate a swift enhancement of power accessibility. Nonetheless, the advantages would be permanent only if lessons regarding power management, contracting, and oversight are thoroughly assimilated. The establishment of a more credible NERC is an essential initial step; nonetheless, the pivotal component is expected to be substantial progress on comprehensive power-sector reforms.

11.6 Capital Accessibility

Access to credit at reasonable interest rates is essential for facilitating investment in renewable energy, whether at the home level or in large-scale generation. The predominant portion of expenses related to any renewable energy producing system is incurred upfront. In battery systems, substantial expenditures arise after five years when battery replacement is necessary, but other components, such as panels, are anticipated to endure for 15 to 20 years or longer. The durability of renewable energy systems is essential for calculating electricity prices and is key to rationalising the initial higher installation expenses.

Sufficient capital is essential for overcoming the 'payback period' in financing renewable projects. This refers to the duration necessary for savings from 'free' renewable electricity to surpass the expenses associated with grid or generator power, which entails consistent billing or fuel requirements. Nonetheless, if the primary source of capital is loan financing and interest rates are prohibitively high, the expenses associated with the loan constitute a significant component of the total cost. In Nigeria, the prevailing interest rates commence at approximately 25 percent annually, accompanied by stringent collateral requirements, presenting a significant challenge. The necessity for accessible loans has been acknowledged for an extended period in Nigeria. The Bank of

Industry is progressively committed to provide loans at a low interest rate of 7 percent per annum or below. Nonetheless, this is inadequately actualised at present, hindered by obstacles in financing availability and adoption.

Alongside low-interest capital, numerous other critical measures must be implemented concurrently. Renewable energy providers must generate significantly more comprehensive cost analyses and pragmatic payback timelines for the entire spectrum of installations, from generation facilities to residential systems. For domestic or independent systems, the complexity is minimal; yet, publicly accessible data remains limited. There is an urgent need for additional information regarding consumers' willingness and capacity to pay bills, enabling both prospective investors and customers of renewable systems to clearly understand the anticipated costs and advantages. Loans will be employed just when enhanced access to cash is accompanied by reliable information and options.

The Views of the Nigerian federal government is that considering the substantial capital expenditures and extended timelines necessary for the development of commercial power generation via solar, wind, nuclear, and biomass, the Federal Government will concentrate its development initiatives on hydro, coal, and natural gas. The potential of natural gas will be recognised, and incentives will be offered to investors to fully harness this resource.

This article aims to investigate the current state of renewable energy in Nigeria, analyse the factors contributing to the sector's underdevelopment relative to other nations, and evaluate increasing evidence of the possibility for renewable energy to assume a significant role. Certain emerging recommendations are very straightforward to encapsulate:

- Pilot programs have illustrated the potential of renewable energy in Nigeria, along with certain persistent problems.
- Ongoing advancements in technology and fluctuations in costs have generated significant potential for interventions of both local and large scales.
- Strategically developed initiatives in markets, education, and finance are now substantiated investments for renewable energy to realise its promise in Nigeria.

Table 2: Challenges and Responses Regarding the Costs of Renewable Energy in Nigeria

Challenge	Response
High initial capital cost of installing renewable energy—whether wind, solar PV, hydro, or solar thermal.	The upfront capital investment cost has some advantages in Nigeria— there are no questions about the ongoing financial and stability issues of fuel and pipelines.
Solar and wind power are clearly better suited to specific parts of Nigeria for the most competitive solutions.	The areas with overwhelming solar potential (northern Nigeria) are very poorly served at present, and seem likely to face very high transmission costs from growing power generation areas in the Niger Delta.
Renewable energy installations have tended to be relatively small compared to conventional grid generation.	Smaller installations near to target communities should mean faster deployment and much lower transmission losses than distant gas- powered options.

Grid-level renewable energy is not an ‘always on’ generation solution. Both solar and wind require complementary generation.	Nigeria’s power shortages are so acute that this may be an acceptable shortcoming initially. As the grid improves, Nigeria has a wide range of sources that should complement renewable sources well.
The feed-in tariffs used as a tool in other countries could prove expensive at a time when Nigeria has difficulties funding infrastructure.	If structured correctly, a green feed-in tariff could prove attractive to agencies such as the World Bank, with a good potential match in the longer term between affordable interest rates and economically sensible green outcomes. The existing cost of power to the private consumer is extremely high, making even the more expensive renewable options competitive.

Regrettably, the actionable measures necessary for an improved energy future in Nigeria, characterised by a robust renewable industry, are considerably more complex to condense into a succinct list of bullet points. While the goals for certain critical phases can be articulated clearly, the process will likely entail the integration of a multifaceted array of stakeholders, funding, education, and technology. Certain challenges may be addressed alone; however, numerous others necessitate effective coordination and teamwork. The notable failures of questionable solar initiatives, which entail substantial government expenditure, illustrate that renewable energy necessitates essential proficiency in planning and development for success.

In addition to proposing a modification in the government's main policy attitude, it indicates the relatively preliminary measures that could be achievable with minimal governmental investment, potentially yielding significant benefits for Nigerian households and fostering wider acceptance in this rapidly evolving sector. A successful foundation at this level is likely essential for garnering broader support for significant advancements, including informed investment decisions in large-scale solar power generation.

11.7 A Necessity for a Transformation in Energy Policy

Emerging research unequivocally indicates that Nigeria possesses a more substantial array of renewable energy resources than previously acknowledged. Moreover, international research indicates that these resources are rapidly becoming competitive with current electricity sources. The current exorbitant energy costs in Nigeria render renewable energy competitive or superior in numerous specific scenarios, particularly in providing targeted support to individuals with the lowest incomes. Energy policy must recognise that the rejection of renewable energy as a viable short- to medium-term option in the official Energy Road Map was a critical error. This indicates that renewable energy cannot be hastily prioritised; rather, it necessitates methodical policy, research, and financial backing for the advancement of the renewable energy sector. A proposal was formulated in 2005 with the Renewable Energy Masterplan, which ultimately was not implemented. Rapidly formulating and executing a revised strategy for strategic investments in renewable energy, integrating insights from the preceding decade, is an essential initial step.

11.8 Comprehending and Instructing the Market

While government policy is significant, it is essential for government and other stakeholders to recognise that many optimal energy solutions will emerge in the marketplace, where the

government's role may primarily be to mitigate complexities. Renewable energy is already competitive with current sources for numerous requirements, and the primary challenge is to synchronise demands, solutions, and accessible money. Progress will be constrained unless both energy consumers and providers possess a significantly enhanced comprehension of their respective demands and feasible energy solutions.

To facilitate market-driven demand, a prominent array of experimental initiatives and educational programs appears essential prior to broad adoption by understandably hesitant customers. Research is required to analyse household requirements, earnings, and desires. The varied circumstances of rural and urban households, characterised by significant disparities in income and living expenses, necessitate a corresponding array of renewable energy solutions that can be more readily tailored to specific conditions. This data enables renewable energy suppliers and vendors to offer products and systems that align with actual needs.

11.9 Fostering developers, educators, and collaborators

This is considerably more challenging in practice, particularly within a political environment that prioritises local content in industry. Nonetheless, as indicated in the Renewable Energy Masterplan of 2005, there is a necessity for strategic investment in both research and business development to expand and consolidate potential for an emerging industry.

A foundation of local knowledge is essential for the development of practical projects. This could be effectively complemented by international experience, which may assist Nigerian firms and government in keeping pace with the swift advancements in technology abroad.

11.10 Aligning capital expansion with developing capacity

The government's financing in Nigeria's electricity industry has a problematic past, and rampant corruption in the fuel business has tarnished the reputation of subsidies. As emphasised in Section 6, there is an urgent requirement for financing for both consumer and grid-level products. Research conducted with solar industry professionals and consumers indicates that there is no definitive solution for finance; however, the following points are noteworthy:

- Additional capital should not be evaluated in isolation; it will be significantly more successful when assessed alongside other initiatives.
- Business mentoring and strategic guidance appear to be critically required for small and medium-sized enterprises. This should be explored diligently. partnership to augment the capital accessible to enterprises.
- Capital support for installment payments becomes feasible in certain consumer sectors, especially for civil servants and individuals with stable incomes.
- Subsidies for consumer goods should not be categorically rejected. Emerging technologies seem to provide enhanced mechanisms for accountability and assurance that benefits are directed to their intended recipients.
- The government's primary function may be to finance a strategy that ensures accessible capital increases in accordance with the renewable industry's attainment of verifiable milestones. Investors in renewable energy must be assured that accessible financing will persist as they progress.

11.11 Incentives for Efficiency and Demand Mitigation

The strategic plan for Nigeria's power sector, along with the prevailing industrial mindset, is currently focused on significantly augmenting supply. It has been clearly established that the most cost-effective method to satisfy total power requirements is to diminish demand whenever feasible, without detracting from customer experience. In essence, decreasing the consumption of one million users by 10 percent (equivalent to around 500 watts of peak demand) can be more expedient and significantly more cost-effective than constructing an additional 500MW thermal power plant. In the realm of renewable energy, it is prudent to explore ostensibly extreme alternatives—regulatory incentives for small-scale systems or village-level initiatives that operate fully off-grid or maintain little connectivity.

Although formally detached from the conventional electricity industry, those opting for this alternative are making a little yet impactful contribution to diminishing total demand, so enhancing the stability of supply for those connected to the grid. Offering further incentives to a nascent sector may expedite the development of viable off-grid installations, which continue to encounter elevated costs related with emerging technologies and are frequently contemplated for somewhat isolated rural regions with inherent obstacles. Enhancing the efficiency of essential appliances significantly lowers the capital expenditure of a solar system.

11.12 Supply Chains, Customs, and Regulations

The diminutive scale of Nigeria's renewable economy poses considerable challenges for installers, particularly when exacerbated by the widespread availability of inferior items, notably batteries and inverters. Importation has seen theoretical advancements with a zero tariff; nonetheless, numerous and costly hurdles persist for novice importers in practice. The recent experience of a 'Light Up Africa' dealer is enlightening. Customs officers initially classified integrated solar lights as lanterns, imposing a 35 percent duty, and subsequently applied additional charges that escalated the total importation cost to 100 percent of the original price.

This circumstance appears to be ordinary but is partially attributable to entrepreneurs with insufficient business acumen who may also lack the networks to navigate such challenges effectively. For low-income Nigerians to benefit from renewable energy technology, it is essential that pertinent government entities acknowledge this sector as one deserving of support, necessitating a favourable interpretation of rules at all levels.

The government could contemplate a comprehensive interpretation of solar and energy-efficient products to incentivise the late entry of complementary products into the mass market in Nigeria. Appropriate possibilities appear to include all deep-cycle batteries, inverters, energy-efficient refrigerators, low-energy air conditioners, low-energy light bulbs (particularly LEDs), and more low-energy devices as they become available.

Given the escalating issue of inferior components, it may be prudent to propose that Nigeria establish guidelines for imported solar products. Currently, both customs and other governmental agencies lack the capability to credibly test or certify products. This area should undergo meticulously planned development, with regulation introduced only when the government can clearly execute policies both equitably and efficiently, without imposing excessive costs on legal

suppliers. Consequently, the involvement of non-governmental entities in cultivating respectable brands and reputations becomes increasingly vital.

State governments, whose rural regions and low-income citizens could gain from suitable low-energy products, should contemplate significantly cutting operational expenses for renewable energy enterprises. The numerous municipal fees and often unwarranted harassment of small businesses by different local government entities constitute a substantial obstacle for small and medium-sized enterprises in the renewable energy sector. Mitigating these obstacles would provide a favourable impetus for swift growth.

Ultimately, the government could assume a crucial regulatory function in anticipation of future developments. Building standards in Nigeria are inadequately enforced, however appear to be progressing in certain regions. Nigeria ought to establish building standards that, while avoiding excessive costs, encourage the integration of low-energy concepts throughout all phases of development. These laws may be incrementally enhanced as diverse solutions become increasingly viable and accessible at reasonable costs.

11.13 Government as an Advocate for Renewable Energy

A primary objective of the electricity sector reforms is to eliminate government involvement in operations and ownership, relegating its role predominantly to regulation. This policy is based on the state's catastrophic management of the industry and investment during the last forty years. Consequently, advocating for government engagement in the renewable energy sector should be approached with prudence.

The government can clearly target certain sectors to rectify financial deficiencies. This should ideally involve close engagement with highly trained partners utilising models that incorporate the extensive lessons learnt from worldwide experience over the past two decades. The specified locations encompass:

- Elevated capital expenditure for small residential and commercial installations, coupled with challenges in securing cheap financing.
- Financial assistance for emerging technologies in which private investors may exhibit insufficient experience and confidence, with solar thermal serving as a quintessential example.
- Capital expenditures for established renewable technologies, including solar photovoltaic and wind energy, in suitable places.

The federal government currently funds numerous solar PV systems via the Energy Commission of Nigeria, NDDC, and other entities. Nonetheless, as detailed in Section 5, there is an imperative necessity to evaluate the quality and medium-term results of these pilot programs. Government-sponsored pilots remain valuable for establishing new technologies; nevertheless, they must have a much reduced failure rate compared to the current standard.

Considering the magnitude of federal and state governments, together with their services, inside the Nigerian economy, there are clear advantages for state entities to progressively implement renewable and low-energy technology. In certain regions, there have been tentative measures taken, such as the implementation of low-energy lighting policies; nonetheless, significantly more action is required.

Given that state services frequently experience persistent funding deficits for power, largely reliant on generators like other entities, there are clear advantages in transitioning more services to renewable energy whenever possible. Considering recent developments, it is imperative to ensure that any conversion is both economically viable and executed by credible firms capable of proposing solutions tailored to specific local requirements.

Two preliminary steps exist:

- a) Initiate partnerships that develop best practices for many critical sectors (e.g. educational institutions, healthcare facilities, governmental edifices) of diverse magnitudes in prominent places.
- b) Expedited research that delineates suitable goals and immediate gains for renewable energy and energy-efficient alternatives, accompanied by essential guiding principles for subsequent actions.

The government has a significant role in both endorsing and actively engaging in public education regarding energy. For the potential benefits of renewable energy and enhanced efficiency to be fully exploited, communities, businesses, and the public must be much better educated about the fundamentals of energy consumption. The secondary school education project launched by the Lagos State Government, incorporating an online component and emphasising energy saving, exemplifies a commendable effort that could have numerous beneficial ripple effects. Incorporating teaching on energy matters, especially renewable energy, into school curricula and significantly increasing the availability of written resources appears to be a wholly suitable responsibility for the government.

Educational programs should extend beyond schools to encompass a diverse array of adult audiences. Innovative measures, like collaborations with churches and mosques to showcase sustainable energy alternatives, should be contemplated alongside other possible promotional avenues. The government must evaluate the role of renewable energy in the tertiary sector, where substantial investment in teaching and research is essential. Practitioners have accurately recognised the pressing demand for proficient technicians, a necessity that will intensify if the sector is fostered to evolve. Nonetheless, with the argument for expansion, there exists a valid rationale for investing in each of the following:

- Technical training for technicians aimed at individuals with prior electrical experience (generator suppliers and repairers).
- Professional development for solar and renewable engineers will necessitate international scholarships until local capability is established.
- Facilitating reputable institutes to investigate renewable energy, emphasising the timely implementation of optimal technology for Nigeria.
- Diligent cultivation of local manufacturing, maintenance, and support facilities that should progress alongside the increasing familiarity with emerging technology.

12. CONCLUSION AND RECOMMENDATIONS

Formulate cohesive strategies for renewable energy planning and investment.
The federal government must enhance its current activities by formulating a cohesive renewable

energy strategy and implementing a substantial escalation in funding for research, market development, and regulation of renewable energy.

Facilitate incentives for the adoption of renewable energy.

The government should contemplate incentives, potentially via a feed-in tariff, for at least one significant trial project of solar thermal power generating in northern Nigeria.

Guarantee enough and cost-effective capital funding.

Systematic expansion of low-interest capital finance for renewable energy is essential, with capital availability increasing in accordance with industry growth.

Enhance public comprehension of renewable energy.

Stakeholders in the renewable sector and government must invest substantially in public education to enhance consumer and policy decisions and to dispel prevailing biases against the industry.

Foster cooperation between renewable energy developers and policymakers.

Policymakers and renewable energy developers must collaborate closely to establish optimal service practices in rural regions, notably with education, healthcare facilities, and water supply.

Instruct on energy use and efficiency.

Energy utilisation, namely energy efficiency and renewable energy, must be integral to the educational framework as promptly as possible, aiming to transform public behaviour and enhance engagement in the burgeoning renewable energy sector.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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DESIGN, SIZING PROCEDURES FOR STAND-ALONE PHOTOVOLTAIC SOLAR WATER PUMPING SYSTEM

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ABSTRACT

Photovoltaic solar energy conversion has become dependable energy source worldwide for provision of electricity for both domestic and commercial applications. However, one impediment in the use of this energy source is lack of proper system design. The consequence is failed projects especially in the rural areas of developing nations like Nigeria. This work provides a simple approach for designing standalone solar water pumping system in for rural communities. In the absence of accumulated solar data over time in the rural communities in Benue State, model equations that provide good approximations are employed in few steps to design a solar water pumping system for water provision in rural communities.

1. INTRODUCTION

Water is a very essential and vital throughout the world. Water is needed for household needs and for irrigation in order to provide the world's ever-growing population with enough food (USGS, 2018). Irrigation is the controlled application of water for agricultural purposes to provide water needs that are not met by rainfall. In Nigeria, a large percentage of land is devoted to rain-fed production, while a small percentage of land is irrigated (FAO, 2020). Nigeria's rain-fed agricultural systems will need better irrigation systems to improve crop yields since most farmers resort to manual means of crop irrigation when there is no rain. More frequent droughts and water shortages represent a big risk to livelihoods and food security, especially for the most vulnerable populations in rural areas (AfCFTA Workshop, 2024). In the Karshi, Abuja, community, a significant percentage of the population earns their living from agriculture. Many

small-scale farmers work all day to provide food for their own families and selling produce when there is surplus. These farmers struggle to obtain enough water to irrigate the crops, thus a more sustainable solution for small-scale farmers' irrigation systems will focus on using reliable, clean-energy solutions. For this purpose, this work developed practical design and procurement considerations to employ photovoltaic (PV) modules to power an irrigation pump lifting water from a well to an elevated storage tank.

2. LITERATURE SURVEY

For irrigation, motor-driven pumps are used to raise water from a lower to a higher level, from which it flows by gravity through channels to the fields. Most water pumping for irrigation purposes is powered with fossil fuels (diesel or petrol). Petrol-fueled pumps are a very common option for smallholder agriculture and are characterised by low initial costs, low weight, a comparatively short lifespan, high fuel consumption, and high maintenance requirements. The diesel-fueled pumps are very popular among farmers because they are easy to work with, deliver water to plants faster, due to the ease of work for farmers and the faster delivery of water to plants, and last much longer than petrol-fueled pumps. The disadvantages of fossil fuels are well known. While diesel motors have an initial low cost but fueling, repair, and maintenance causes operation costs to increase over time. In addition, they can lead to pollution of soils and groundwater. A solar-powered pump is different from conventional pumps because it does not need fuel or electricity from the grid or a generator to operate. A solar-powered pump can be a cost-effective, environmentally-friendly, and low-maintenance way to meet water needs for agricultural irrigation and are particularly suitable for remote areas with no or unreliable power grid.

A solar water pumping system (SWPS) uses PV panels to drive a pump that sucks up water from a particular source and discharges the water either to an over-head tank or piping within a long distance where water is needed (Omoraka et al., 2023; Odesola and Bright, 2019). Solar-powered irrigation systems (SPIS) have been practiced since the 1970s (Gualteros and Rousse, 2021; Bahadori, 1978; Dannies, 1959; Pytilinski, 1978; Wenham, 2007; Hartung and Pluschke, 2018; IRENA and FAO, 2021) and has been considered a technology change in the irrigation and agriculture sectors. In fact, it is only the energy system that changes and not a mechanical system, of the irrigation system and therefore the classification is driven by the typology of energy systems (Shirsath et al., 2020). With recent improvements in efficiency and innovations in delivery and financing models, its attractiveness has grown, as has its deployment (Hartung and Pluschke, 2018). Solar pumps have several advantages that make them a good choice for modern farming. They do not contribute to CO₂ emissions, are simpler to design, and have fewer moving parts; thus reducing malfunctions and repair costs. There are also challenges and considerations that farmers need to know about when implementing a SPIS. One of the primary challenges is the high initial investment cost for equipment and installation for smallholder farmers with limited financial resources. However, it is important to consider the long-term savings and benefits these systems offer, as they often outweigh the initial investment. Besides the high cost of solar irrigation systems, other challenges are access to finance, especially for small-scale farmers, as well as the availability of good products and services and that can operate during daytime.

Many successful SPIS have been implemented in different regions and for variety of farming practices. For example, they have been adopted by large-scale commercial farms, such as the Bowery Farming facility in New Jersey, United States. Bowery Farms has been able to grow a variety of crops year-round using solar panels and advanced hydroponic technology. Additionally, the farm's carbon footprint is reduced, making it a sustainable and environmentally friendly operation. Another successful case study is the Solar Pump Irrigators' Cooperative Enterprise (SPICE) in India. SPICE is a community-based

organization that helps smallholder farmers use solar irrigation systems. SPICE has helped farmers switch from diesel-powered pumps to solar-powered systems by offering financing options and technical support. Farmers have been reporting increased crop yields, reduced operational costs, and better access to water. After the introduction of the SPIS, farmers in Bihar, India, were able to switch from deficit to full irrigation, which improved plant health, increased crop yields, and extra income from selling the excess produce (GIZ, 2013). In the Sudano-Sahel area of Northern Benin, SPIS was installed in vegetable gardens formerly watered with cans and hauled water. This allowed the women farmers to become net producers of vegetables, make money from market sales, and increase their household nutrition intake and food security (Burney et al., 2009). In Maharashtra, India, replacing diesel pumps with SPIS helped improve the on-farm economic benefits. These were in part due to micro-irrigation practices integrated with SPIS, which allowed for reduced input costs, increased productivity, and higher yields (Honrao, 2015).

Various studies have compared the costs of using conventional and alternative energy technologies for irrigation water pumping at the site scale (Girma et al., 2015; Hossain et al., 2015; Kelley et al., 2010; Lorenzo et al., 2018). There are big differences in investment and running cost when comparing between solar-powered, fuel-powered, and electric powered systems. The solar-powered system was much more expensive than the other two systems. But it could still be justified when compared to the fuel-powered system, because of the high running and maintenance costs as well as the short life of the fuel pump. It is harder to justify the economic advantages of the solar system compared to the electric pump. However, since electricity in Nigeria is not always reliable, farmers should invest in a solar system if they can afford it (Oba, 2018).

Considering that all systems use a lot of water, the environmental impact of water collection is about the same. However, the remaining environmental impact is different (Oba, 2018). The CO₂ emissions from the SWPS are negligible. On the other hand, there is a significant amount of emission from the use of petrol. By burning 1 L of petrol, kg of CO₂ which is released in the atmosphere (U.S. EIA, 2015). In summary, using solar water pumps is a good way to water plants without harming the environment. Solar-powered irrigation systems are good for small farmers because they save money on fuel and maintenance. They also have a good return on investment, which can last for many months or years.

The assessment of crop water needs can be done by calculating irrigation water requirements (IWR). The net IWR is the amount of water required for crop growth. It depends on the cropping pattern and the climate. Each crop has its own water requirements, and multiple cropping periods have to be taken into account when calculating crop water requirements for each crop (Frenken and Faurès, 1997; Sass and Hahn, 2020). For solar irrigation, data on water needs, access to and availability of groundwater is often needed. According to Sass and Hahn (2020), the data required to design a solar-powered irrigation system are: crop data (crop type, growing season, crop rotation, and water demand); water data (availability of water); site data (longitude, latitude, water source, and pumping head); and meteorological data (insolation and temperature). Therefore, the objective of this study is to design an efficient solar-powered water pumping system that would be built for irrigation systems on farms in Karshi-Abuja.

3. THE REVOLUTION OF SOLARPUMPING

Solar photovoltaic water pumping (SWP) uses energy from solar photovoltaic (PV) panels to power an electric water pump. The entire process, from sunlight to stored energy, is elegant and simple. Over last seven years, the technology and price of solar pumping have evolved dramatically - and hence the

opportunities it presents. *SWP system capacity and ability have expanded.* Early solar pumps had limited performance and were restricted to pumping installations with a shallow water source and a low water demand. Today, pumps can reach deeper wells (500 meters (m), compared to the previous 200 m) and push larger volumes of water ($1,500 \text{ m}^3/\text{day}$, compared to the previous $500 \text{ m}^3/\text{day}$ at low head). Efficiencies have also increased considerably. New pump and motor designs have increased water outputs over the entire pump range, as Figure 1 illustrates.

Prices of photovoltaic (PV) panels have dropped exponentially. High demand for PV modules for grid-tied applications has resulted in massive economies of scale in production as well as competition among vendors. The commodity price of silicon, the key material, has also dropped substantially.

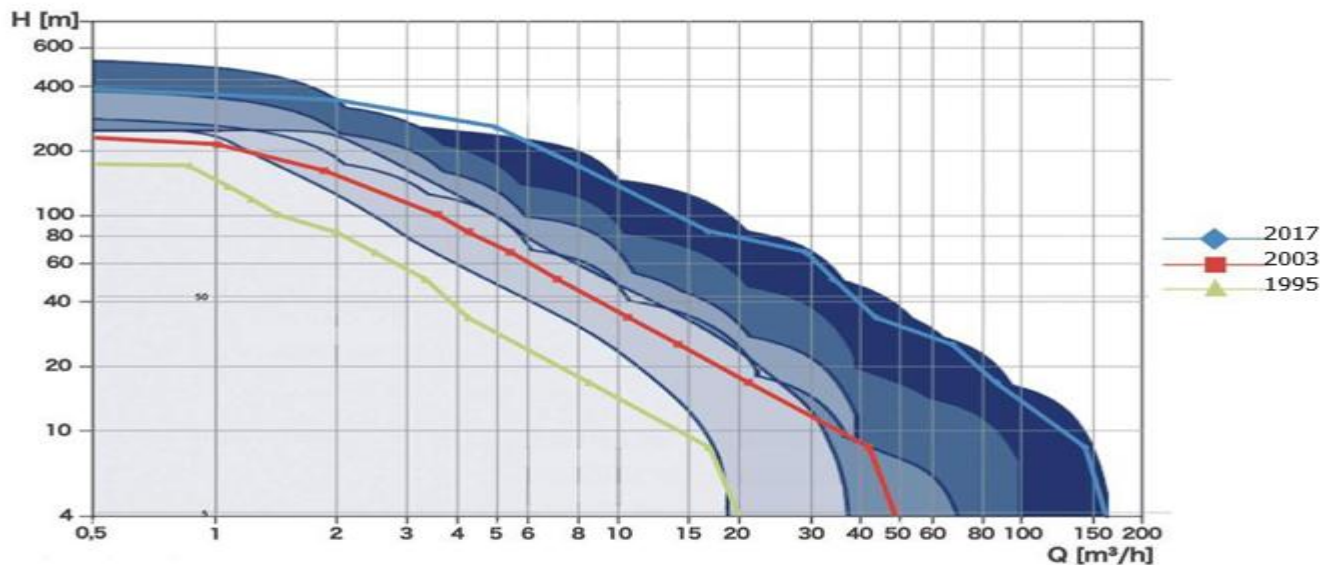


Figure 1. Solar pump capacity has increased due to technology innovations. Image credit: Grundfos.

Solar modules once cost around \$5/Wp (watt-peak); now, they are less than \$0.75/Wp (ex-factory) as Figure 2 indicates. These reductions have made larger SWP systems possible where previously the capital cost priced them out of range. Many reasons accounts and some are listed here:

1. *The number of SWP manufacturers and suppliers has increased.* Old monopolies have been broken, and although the technology leaders continue to innovate, competition is fierce on price, performance, and quality.
2. *SWP is cost-competitive with diesel and wind pumps in all size ranges.*
3. *SWP is being mainstreamed and awareness is growing.* Good news travels fast, and markets are already demanding SWP in place of conventional pumping solutions. Further opportunities are arising as intensive awareness campaigns support and elaborate on the details of system performance and savings. Retrofits to diesel pump systems represent a market for further potential savings.

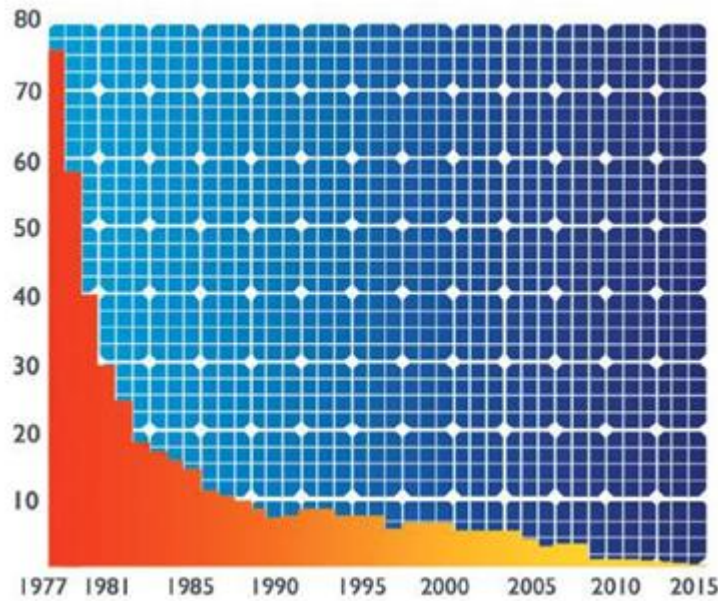


Figure 2. Falling prices PV cells (in \$/watt) over time.

3.1 Solar pumping's current applications

The highest demand is within rural off-grid areas, currently underserved, or served by costly fossil fuel-driven pumps. The potential applications include:

- Potable water supply for institutions (traditional niche market for schools and health clinics)
- Community-scale water supply schemes (larger village schemes)
- Livestock water supply (individual or communal)
- Small-scale irrigation (individual farmers or cooperatives)

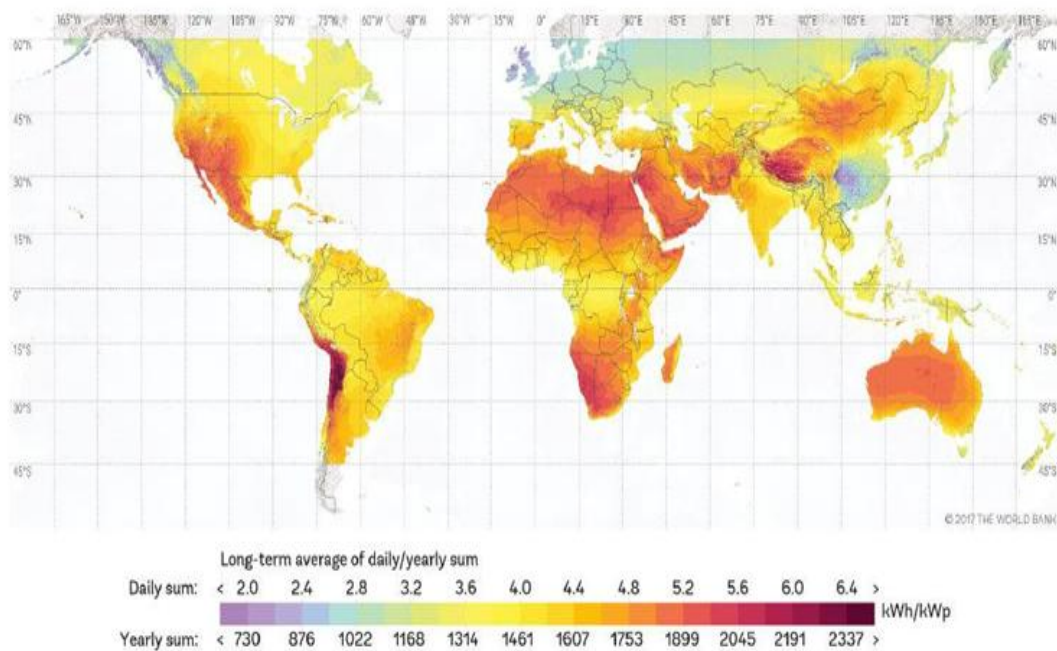


Figure 3. Global solar radiation map. Source: The World Bank.

Solar pumping is most competitive in regions with high solar insolation, which include most of Africa, South America, South Asia, and Southeast Asia. Although these regions all have high radiation (see Figure 3), the availability and depth of water resources vary significantly. The pros and cons of solar water pumping are listed below.

3.2 Advantages of solar pumping

1. SWP systems consume little to no fuel. By using freely available sunlight, they avoid the constraints of weak or expensive rural fuelsupply networks.
2. Unlike diesel-based systems (i.e., where a diesel generator powers the pump), solar pumping produces clean energy with zero or much reduced exhaust gases and pollutants.
3. Solar pumping systems are durable and reliable. PV panels have a design life of over 20 years, and solar pumps have few moving parts and require little maintenance (unlike diesel pumps).
4. Solar pumping systems are modular so can be tailored to current power needs and easily expanded by adding PV panels and accessories.
5. Properly installed solar systems are safe and low risk due to low system voltage. Adequate protection minimizes fire risk.

3.3 Possible disadvantages and mitigation

- a) Solar pumping systems have high initial capital costs, which can be discouraging. However, component prices are dropping substantially and investment payback is quick thanks to vast reductions in fuel usage (as detailed in Chapter 2).
- b) Water tank storage is preferable to batteries, but still expensive. Hybrid solar/diesel pumping can reduce the need for storage and hence costs.
- c) Solar pumps still require some servicing, and specialized technicians/providers may be difficult to access in some areas. This is gradually improving.
- d) Panel theft can be circumvented by sensitizing communities and providing simple antitheft measures.
- e) SWP can lead to excessive groundwater extraction because operators face near zero marginal-cost of pumping ground- water.

3.4 Basic configuration and advantages of solar pumping systems

A solar-powered water pumping system is like any other pumping system, except its power source is solar energy. Solar pumping technology covers the entire energy conversion process, from sunlight, to electrical energy, to mechanical energy, to stored energy. The process is elegant and simple.

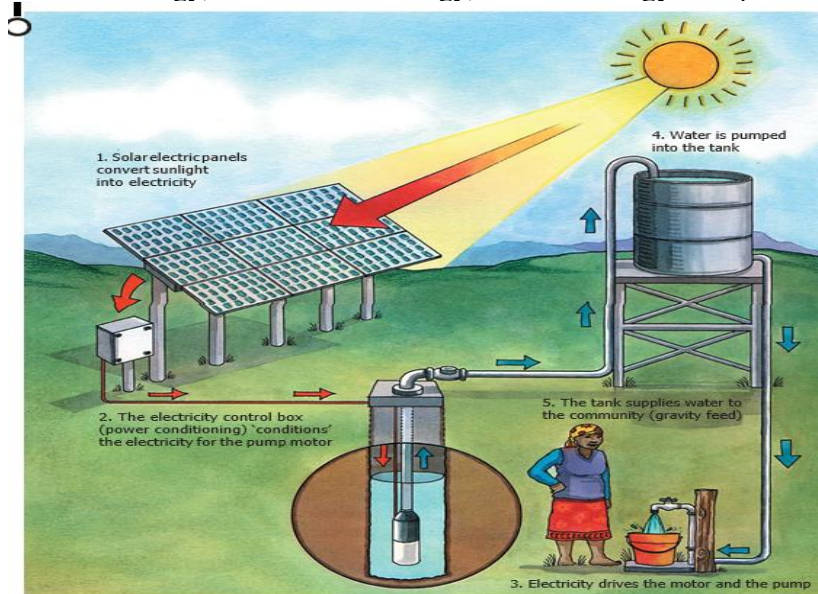


Figure 4. Solar water pumping system. Image credit: Energy and Development Group.

4. ECONOMIC BENEFITS

4.1 Life-cycle cost analysis

There are several technically viable options for new pumping systems, generally distinguished by their energy source—diesel pump, wind, solar, etc. Cost-benefit analysis (CBA) is often used to assess the economic merits of alternative investment options. Pumping systems typically have a 20-year lifespan, and over that period they incur various costs, some at the outset, and others at different times throughout the system lifetime. Consideration of all costs incurred during the system lifetime is often referred to as a life-cycle cost analysis (LCCA). LCCA is particularly important for renewable energy projects because of the high initial investment costs. More conventional options based on fossil fuels may appear cheaper due to lower initial costs; however, operating costs can be considerable over the project life.

Although pumping systems have myriad costs during their lifetime, a proper LCCA would assess at least four key cost elements:

- Initial costs with capital expenditures (CAPEX) and installation/commissioning.* These mostly consist of the acquisition of equipment for the solar pump system: PV panels, pump, control system, pipes and fittings, wiring, etc. Initial costs also include design engineering, system installation, commissioning testing and inspection.
- Operation and maintenance (O&M).* Operation costs are labor and energy costs related to a pumping system's operation. They can vary widely depending on the system's complexity and duty. For example, a hazardous duty pump may require daily checks for emissions and operational performance, whereas an automated nonhazardous system may only require limited supervision. Security and managerial costs are also included here. Maintenance costs comprise all costs entailed in keeping the system functional, including routine activities (e.g., cleaning solar panels) and small repairs to faulty components. System design can influence O&M costs through construction quality, components used, and ease of access to spare parts.
- Energy.* System energy consumption is often one of the largest cost elements in the LCC, especially if the pump runs more than 2,000 hours per year. Solar pumping systems have lower energy supply costs than systems based on fossil fuels, such as diesel.
- Capital replacements.* Some major parts of a pumping system have a shorter design lifetime than that of the overall system (often 20 years), requiring capital replacements along with the associated costs. The pump, for example, often needs to be replaced after 7–10 years.

4.2 Example from Nigeria

An example from Nigeria illustrates the economic benefits of solar pumping. Exactly 418 existing operational diesel pump water schemes (i.e., water pumps running on diesel generators) in rural areas were identified. Data were collected on these schemes to compare the LCC of a typical system with the LCC of solar pumping. Figure 5 shows the yearly costs of a typical diesel generator pump system.

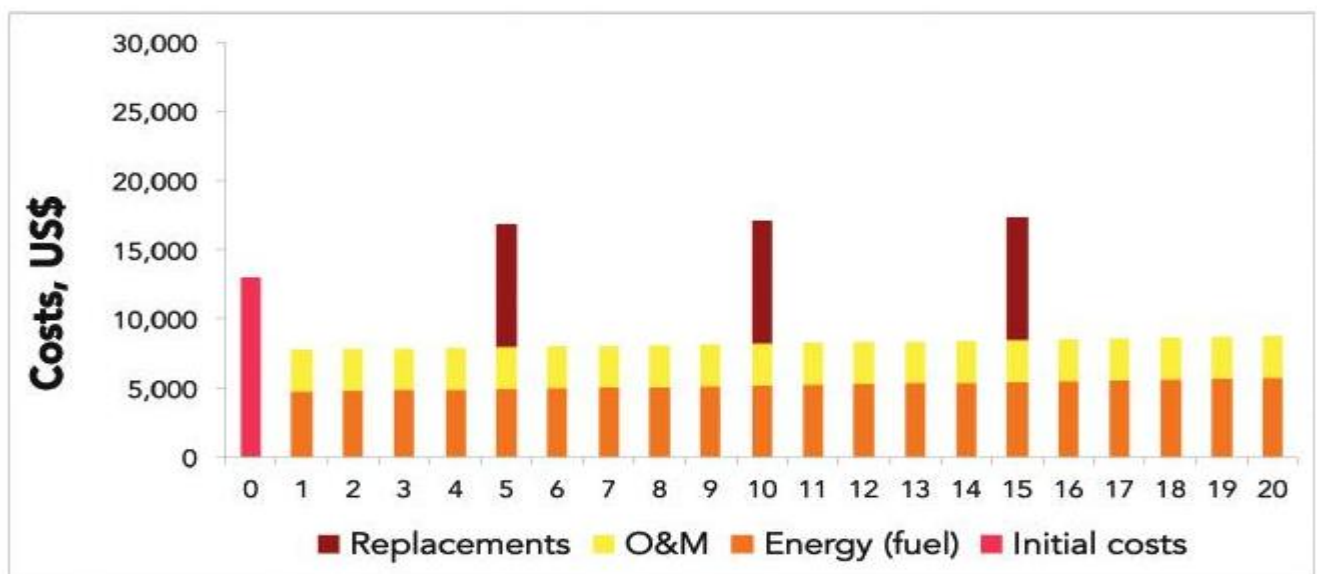


Figure 5. Yearly costs of a diesel-based pumping system.

The initial system costs are around US\$13,000. Thereafter, the system incurs substantial annual costs for diesel fuel (the average yearly expenditure in fuel is over US\$5,000, or 40% of initial costs), as well as periodic replacement costs.

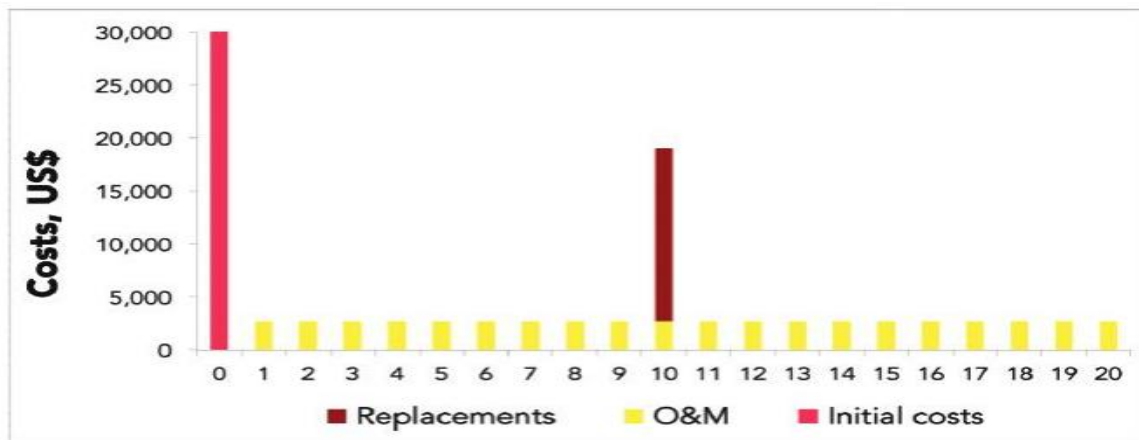


Figure 6. Yearly costs of a hypothetical solar pumping system.

By comparison, Figure 6 represents the yearly costs of the average solar pumping system. Although initial costs are higher (around US\$30,000) and there would be significant expenditure in year 10 to replace the pump, these costs are more than compensated for by the vast reduction in energy costs. If the diesel-powered pumping scheme in Figure 5 converted to solar, the life-cycle cost would be about US\$59,000, 36% down from US\$93,000 for the diesel pumping (see Figure 7).

This would translate into a price reduction from US¢40/m³ to US¢25/m³ for water extracted. Investment in solar pumping for these schemes would yield an internal rate of return (IRR) of 34% and be paid back within 3.6 years. A more thorough LCCA that includes environmental costs from carbon dioxide (CO₂) emissions and lost production costs from system downtime would demonstrate even higher benefits since solar pumping is more attractive than diesel on both counts.

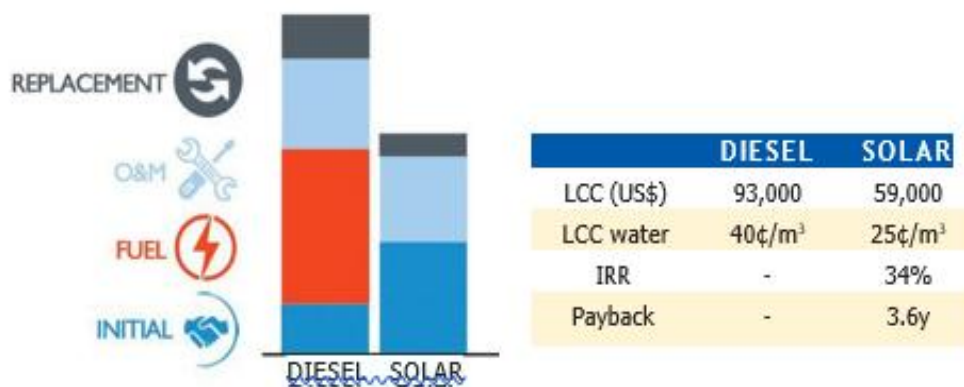


Figure 7. Economic comparison of diesel with solar pumping.

Although this is only an example, the findings of the analysis are in line with those from other studies regarding the economic benefits of solar pumping, in particular, compared with diesel pumping. Such benefits will tend to increase further as the price of solar components drops due to technological advances.

5. MAJOR SYSTEM COMPONENTS

A solar pumping system consists of PV modules, a pump set, a storage tank, electronic components, and interconnected cables (see Figure 8). Electronics normally include an inverter, power conditioner or pump controller, controls/protections, and water sensors. This chapter describes in more detail the major components used in solar pumping systems.

5.1 PV modules

The energy and power for driving an SWP system comes directly from an array of solar modules of the correct size and specification. The elementary component of a solar module is the solar photovoltaic (PV) cell. The cell directly converts solar radiation into electric current, through the photoelectric effect. The ratio of electric power produced to radiation received is the solar PV cell's efficiency. For example, if a cell generates 0.15 kW of power for each kW received from the sun, its efficiency is 15%. The semiconductor materials most commonly used in commercial PV cells are crystalline silicon. These modules are either monocrystalline silicon modules, where each PV cell has a single silicon crystal; or polycrystalline modules, where each cell has multiple crystals (see Figure 9).

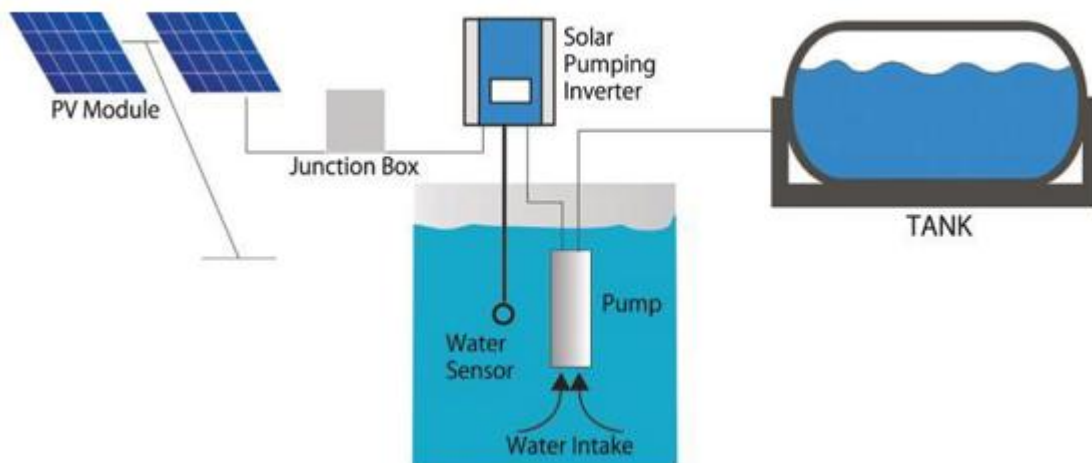


Figure 8. Basic elements of a solar pumping system, Source: Zhuhai MNE Technology Co., Ltd.



Figure 9. Mono- (left) and poly- (right) crystalline solar panels; Source: York Solar.

Mono-crystalline modules are more efficient than polycrystalline ones (16–17% compared to 14–16% in commercial applications). PV modules are rated according to their power output, based on a solar irradiance of $1,000 \text{ W/m}^2$ at a specified module temperature. Panel output data includes the peak power (maximum power generated by the panel, often referred to as watt-peak [Wp]), voltage (volts [V]), and current (amps [A]). In addition to irradiance, PV module temperature affects the amount of power produced, with higher temperatures decreasing power output. It is therefore a good design practice to ensure good ventilation of the modules to limit their temperature increase.

A challenge in many countries has been the lack of quality regulation, leading to an influx of cheap, substandard, and counterfeit products in the local market. Purchasers of solar panels should thus seek quality assurance, as there are now well-developed global standards and testing procedures for panels, notably from the International Electrotechnical Commission (IEC) or similar organizations.

The main global standard for crystalline silicon modules is IEC 61215, which, like similar standards, is awarded largely based on tests administered to samples of modules produced. Since modules cannot be tested throughout their 25-year life time, accelerated stress testing is performed. One of the main tests is the verification of the nominal peak power that a PV module can deliver under standard testing conditions (STC), which include 1 kW/m^2 of insolation perpendicular to the panels and 25°C of PV cell temperature.

Quality of solar modules, and matching of solar module performance is especially important in SWP systems consisting of large arrays of modules connected in series, where array performance, hence SWP performance, depends on the performance of the weakest module. Even one module with inferior output can have a devastating effect. The commissioning of a SWP system should identify such weaknesses through I-V curve scanning of the array.

Pumps and motors

Pumps physically lift water from source to point of use/storage. Technological progress has radically improved pump performance over the years, with pumps now available for pumping ranges up to 500 meters deep or $150 \text{ m}^3/\text{h}$, as represented in Figure 10.

Water pumps are driven by electrical motors, which convert electrical energy (produced, in the case of solar pumping, by PV panels) into mechanical energy. Most motors typically run on either direct current (DC), where the electrical flow does not switch direction periodically in the wires; or alternating current (AC), where it does.

DC motors are appealing for solar pumping because PV modules producing direct current can be directly coupled to the motor with limited power conditioning. This makes them an economical option for systems with low water demand and a short cable distance between the PV panel array and the motor. For long-distance cabling, however, low-voltage DC motors are not suitable because of power loss in the cable. DC motors are currently not available beyond the 5 kW threshold. AC motors can be used in larger SWP systems, although they require a DC/AC inverter.

Solar pumping systems use two main types of pumps: positive displacement and centrifugal. Positive displacement pumps are further divided into volumetric and helical rotor pumps. Broadly speaking, positive displacement pumps are suitable for lower flow rates and medium to high pumping heads (30–250 m), whereas centrifugal pumps are suitable for high flow rates and lower pumping heads (10–120 m). Within positive displacement pumps, helical rotor pumps are especially suitable for operation with low and variable solar radiation levels, since they can pump at low speed without loss of efficiency, unlike centrifugal pumps, which do not produce any water below a threshold speed and are thus much less efficient at low or fluttering irradiation.

It should be noted that these are generalizations for illustration. The most suitable pump and motor type for any situation should be determined based on manufacturers' catalogues and motor pump manuals, and specifically on pump/motor pair performance curves similar to Figure 10 (characterized to the IEC 62253 standard) to ensure that the pump/motor pair can deliver the required flow against the total dynamic head (TDH)¹.

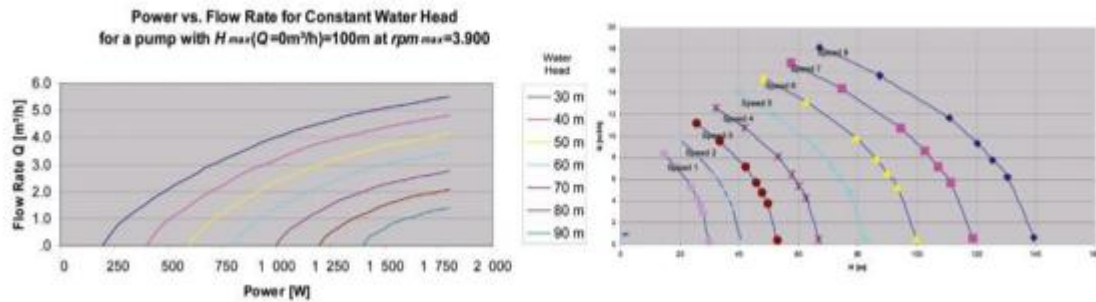


Figure 10. Pump motor characteristic P-Q curve and H-Q curve. Image credit: International Electrotechnical Commission, IEC.

Power conditioners

Power conditioners convert DC power from the solar panels to match the pump motor's requirements. Power conditioners can take several formats: a simple DC-DC converter, a simple fixed-frequency inverter for an AC pump, or a more complex variable speed drive (VSD) in single or three-phase AC power. In general, the power conditioner is matched to a specific pump and optimized to suit the pump performance for array voltage and power. Pump kits from larger pump manufacturers provide an optimized power conditioner and motor/pump as a matched set. Such power conditioners provide change-over between solar supply and diesel engine supply, enabling use in hybrid systems or systems with back-up.

System integrators are increasingly combining third-party power conditioners or programmable VSDs with other third-party motor/pump pairs, and branding them as their own or offering them as original equipment manufacturer (OEM) solutions. Although these solutions may be just as efficient, they have likely been less well tested and the performance depends entirely on the programming setup. In particular, the performance of the controller/motor/pump under intermittent sunshine solar conditions may be substantially lower if not properly set up. For that reason, the testing and characterization of the entire set under the IEC 62253 standard, which can include three test conditions (clear day, cloudy day, and intermittent sunshine), can yield valuable comparative results.

Examples of major solar pump manufacturers include Grundfos (www.grundfos.com), Lorentz (www.lorentz.de), and Mono (www.mono-pumps.com). Suppliers of VSD include:

- ABB ACS355 solar pump drive: www.abb.com
- Vacon 100X drive: www.drives.danfoss.com
- Altivar 312 solar: www.schneider-electric.com
- Solartech solar pumping inverter: www.solartech.cn
- JFY solar pumping inverter: www.jfy-tech.com
- Grundfos renewable solar inverter (RSI): www.grundfos.com
- Lorentz PSK2 solar pump controller: www.lorentz.de
- Invt solar water pump inverter: www.invt.com

6. SYSTEM DESIGN CONSIDERATIONS

The conceptual design of solar pumping systems is best accomplished by analyzing the following seven key parameters:

- a) Water demand
- b) Water source
- c) Design flow rate
- d) Water storage

- e) Total dynamic head
- f) Location of PV panels
- g) Solar resource

This design process is complemented by deeper awareness of the equipment to be used in the system. Thereafter, it should be possible to do a rough SWP system sizing and costing calculation.

Water demand

The design capacity of the solar water system depends primarily on water demand, measured in m^3/day or liters/day (see Table 2). Water is considered for human and/or livestock consumption or for irrigation. Potable water for human consumption in a village/town is estimated from population size and daily per capita water consumption. For example, if the system is to serve a population of 2,000 and the supply standard is 30 liters per capita per day, then system design capacity should be at least 60,000 liters/day or $60 \text{ m}^3/\text{day}$. Similarly, water demand for livestock will depend on livestock type and quantity.

Irrigation water demand assessment is considerably more complex, and depends on area, soil hydration and properties, evaporation rates, crop selection, spacing, crop seasons, irrigation type, etc., and is best determined by an agronomist, to avoid over- or under-estimating water needs, and to determine optimal cropping seasons. The standards used in determining the water demand can usually be obtained from the ministry or government agency for water in the country. Designs typically allow for population growth and seasonality of demand.

Water source

Fresh water is generally obtained through open sources or surface water, such as rivers, streams, and dams; or protected ground water sources such as boreholes and wells. Each is characterized with respect to security of supply, water quality, and replenishment. In general, groundwater is preferred for potable water.

In assessing surface water sources, the following aspects must be carefully considered:

- *Water availability and pumping levels.* Accounting for seasonal variations is critically important, since some sources may dry up, while others may be prone to flooding and high risk. Water level may vary considerably between seasons, affecting pumping head.
- *Water quality.* Debris, silt, and sediment can cause damage to the pump if not properly screened at pump intake.
- Groundwater is a commonly used water source. Groundwater is contained in aquifers, natural underground water reservoirs accessed by wells or boreholes. A pumping test is conducted to evaluate the amount of water that can be pumped from a particular aquifer. The test determines the maximum yield (in m^3/h) as well as the drawdown, or depth to which the water level in the borehole will fall for a given yield and duration (yield per meter of drawdown), while being dynamically replenished by the aquifer. Obviously, a low drawdown is desirable.
- Water demand that exceeds an aquifer yield can lead to over-pumping. Over-pumping is evident from deeper drawdown. This can lead to precipitation of heavy metals and oxidation of iron compounds, potentially causing infiltration of nitrate and pesticides in the water and the formation of ochre, which may clog the pump. This vicious cycle leads to increased service costs for the pump, a need for water treatment, longer-term aquifer depletion, and possibly reduced aquifer life.
- *Design flow rate*
 - In conventional engineering design, a pump's design flow rate is derived by dividing the daily water demand by the total number of pumping hours in a day. Solar pumping applications, however, use the number of peak sun hours to estimate the daily pumping hours.

- For example, in a solar resource that averages $7.0 \text{ kWh/m}^2/\text{day}$, peak sun time is 7 hours/day. For a daily water requirement of $70 \text{ m}^3/\text{day}$, the design flow rate is $70,000 \text{ liters/day}/7 \text{ hours/day} = 10,000 \text{ liters/hour}$. The design flow rate should not exceed the maximum water source pumping rate or yield. The design flow rate is used for future water pressure drop calculations and pipe sizing.

Table 1. Illustrative water requirements use to estimate water demand.

Human consumption (litre/capita/day)			
Urban user		130	
Rural household		80	
Rural minimum standard		20-35	
Notes:			
• Design standards vary from country to country and the needs from location to location. • Irrigation water requirements are especially variable and dependent on local climatic conditions, crop selection, and seasonality.			
Irrigation at crop (m ³ /ha/day)			
Banana, sunflower		40	
Maize, beans, kale, cabbage, lettuce, onion, tomato		15-17	
Potato		10	
Livestock			
Cattle	Cattle	40-50	1/head/day
Sheep	Calf	15-25	1/head/day
Birds	Pig	8-11	1/head/day
	Lactating sow	20	1/head/day
	Piglet	5	1/head/day
	Layers	40	1/100 birds/day
	Broiler	10	1/100 birds/day
	Chicks	8	1/100 birds/day
Irrigation efficiency			
Floor or open channel		40%	
Sprinkler		80%	
Drip irrigation		98%	

Water storage

Most solar pumping systems require water storage capacity to improve performance and reliability. Reliability is improved when a storage tank is used to store water extracted during sunshine hours to meet water needs at night, or in the event of cloudy weather or system downtime.

In general, SWP tanks should be sized to store at least a 2–3-days of water supply (daily demand (m^3/day) $\times$ 3 days = storage volume (m^3)). Field survey data indicate that many SWP storage tanks are too small, and experience water overflows in the daytime and shortages in the evening. Optimal tanksizing must account for the hourly water demand pattern as well as possible insolation variations supplying the tank. Diesel pump systems, or SWP switchable with diesel back-up, on other hand, allow for much smaller tanks for back-up storage since the diesel pump may be run at any time.

Total dynamic head

In pumping systems, “head” refers to the height to which water must be pumped relative to its normal level (e.g., underground). Total dynamic head (TDH) or total pumping head is the sum of three components, as represented in Figure 11.

Dynamic water level (DWL) is the depth of the surface of the aquifer. This gradually increases due to drawdown, hence the term “dynamic.” Discharge head corresponds to the height above the ground of the water surface inside the storage tank (usually 5-10 m). The water is discharged to users through gravity, thus the name “discharge.” Friction head accounts for the friction of the water against the inside of the pipes (both vertical and horizontal). It is typically 10% of the DWL plus discharge head.

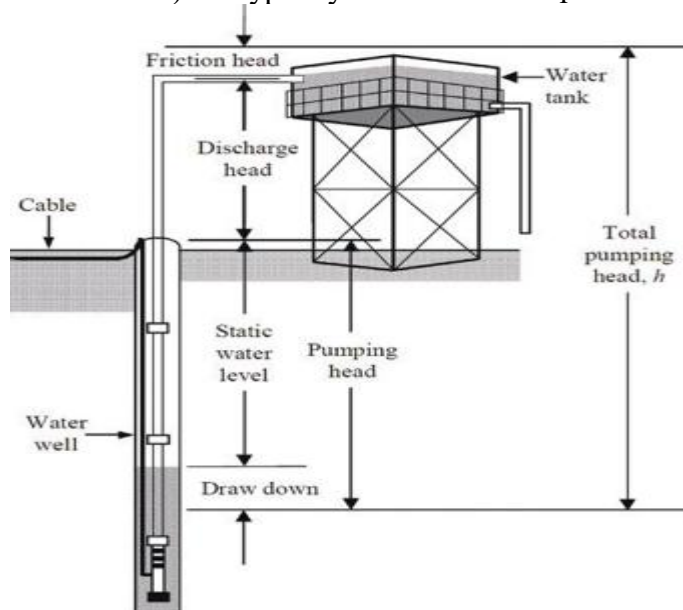


Figure 11. TDH determination in a water well. Source: National Renewable Energy Laboratory.

A pumping test can provide information on the DWL and the discharge head, whereas the friction head can be more accurately obtained from head loss charts for pipes at the required flow rate and pipe characteristics.

Location of PV panels

Although not critical to the initial system sizing, PV panels should be installed close to the pump and water source, equator-facing, at optimal tilt angle to the horizon, and unshaded in any part of the solar array for the solar day. Panels should generally be situated in a secure and safe location. These issues can be fine-tuned during final design and installation, but for purposes of preliminary design, it is conceivable that the solar array would not be closely located to the pump, and thus longer array cables are required, with possible energy losses. This scenario calls for a high allowance for power loss in array cables.

7. SOLAR RESOURCE

Solar insolation is a measure of the cumulative irradiance received on a specific area over a period of time. It is a measure of energy (rather than power), normally expressed in kilowatt-hours ($\text{kWh/m}^2/\text{day}$). The characteristics of the solar resource at the site are critical to system design. Sunshine reaches the earth through radiation. Solar irradiance is the power of solar radiation received per unit area. Irradiance is the instantaneous measurement of power, in watts or kilowatts per square meter (W/m^2 or kW/m^2). Irradiance is affected by the angle of sun, and at any time of day it is highest when a solar module is perpendicular to the incident sun rays. Since the sun's position in the sky changes during the day, irradiance increases during the morning until noon (when it is highest), and then decreases until sunset, since the sun's rays must penetrate more of the

atmosphere to reach the earth (see Figure 12).

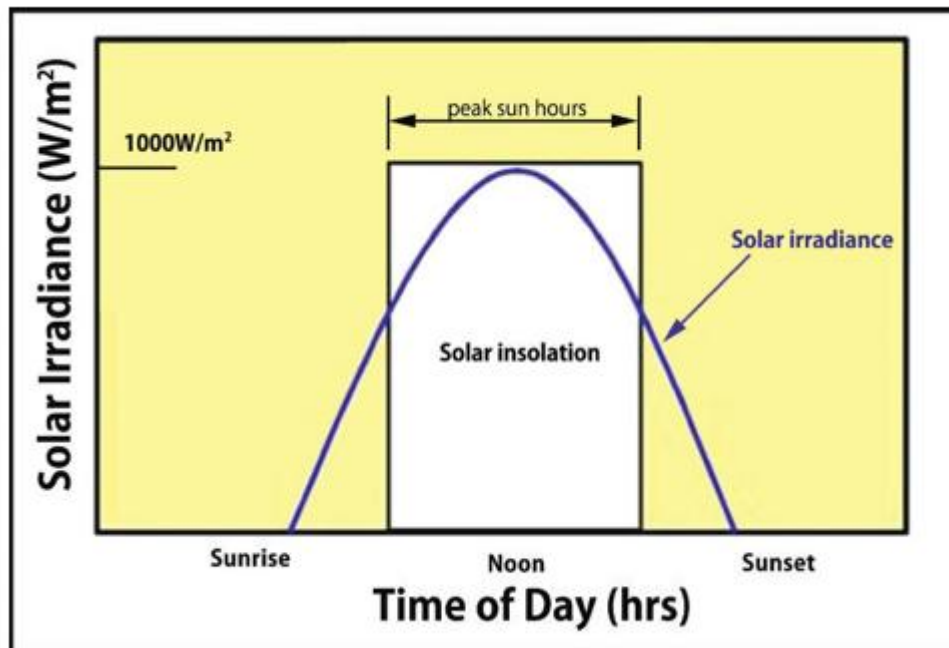


Figure 12. Solar irradiance on a given site during the day, Source: Renewable Energy Primer-Solar.

Solar insolation is effectively equal to the area under the solar irradiance curve. Peak sun hours per day is just another term for solar insolation and is always measured in kWh/m²/day. Solar resources vary from area to area. As Figure 3 illustrates, solar radiation is generally higher in regions near the equator. Factors that affect the amount of solar radiation on a particular area include latitude, prevalence of cloudy periods, humidity, atmospheric clarity, and seasonal variations.

Long-term statistical weather data from meteorological stations is usually provided in the form of monthly averaged data for insolation on a horizontal surface, and includes daily variations of this insolation. Since sizing of SWP systems requires further adjustments and optimizations to this data to account for non-horizontal or tilted solar arrays orientated toward the equator, the complex nature of these calculations and statistical basis of the data suits computer-based sizing approaches.

8. SIZING OF SWP

The use of sizing software is highly recommended; nonetheless. The sizing of SWP system can naturally be estimated using simple formulae, the understanding of which is appropriate for SWP 101. The basic principle for sizing is to create an “energy balance.” Energy balance for a solar SWP system is determined by:

Electrical energy (solar resource, solar array, power conditioner) × motor-pump efficiency = hydraulic energy (volume delivered, head, friction losses).

Electrical energy yield to the motor- pump can be estimated as follows:

$$E_{\text{sys}} = P_{\text{array\_STC}} \times f_{\text{man}} \times f_{\text{dirt}} \times f_{\text{temp}} \times H_{\text{tilt}} \times \eta_{\text{pv\_inv}} \times \eta_{\text{inv}} \times \eta_{\text{inv\_sb}}$$

where:

E_{sys} = average yearly energy output of the PV array, in kWh

$P_{\text{array\_STC}}$ = rated output power of the array under standard test conditions, in kWp

f_{man} = de-rating factor for manufacturing tolerance, dimensionless (100%)

f_{dirt} = de-rating factor for dirt, dimensionless (95%)

f_{temp} = temperature de-rating factor, dimensionless (95%)

H_{tilt} = daily insolation value (kWh/m²/day) for the selected site

$\eta_{\text{pv\_inv}}$ = efficiency of the subsystem (cables) between the PV array and the inverter (98%)

η_{inv} = efficiency of the inverter, dimensionless (95%)

$\eta_{\text{inv\_sb}}$ = efficiency of the subsystem (cables) between the inverter and the switchboard (95%)

Overall efficiency is therefore about 77.4%. Note that cloud cover will further reduce output. Hydraulic energy out of the pump output can be calculated as follows:

$$E_{\text{hydraulic}} = Q \times \text{TDH} \times \rho \times g / 3,600,000 \text{ (J/kWh)}$$

where:

$E_{\text{hydraulic}}$ = hydraulic energy in kWh

Q = daily water output (m³/day)

TDH = total dynamic pumping head (m)

ρ = density of water = 1,000 kg/m³

g = 9.8 kg.m/s²

$\text{Pumping system efficiency}^2 = \text{hydraulic energy} / \text{electrical energy yield}$:

$$H_{\text{motor}} \times \eta_{\text{pump}} = E_{\text{hydraulic}} / E_{\text{sys}}$$

Sizing example

A SWP system for a rural community of 2,000 people must be designed to deliver potable water at the standard 30 liters/capita/day. The tested water source level is at 100 m static head below ground level.

Borehole drawdown is 5 m at 5 m³/hour, and 10 m at 10 m³/hr. Gravity head, or elevation of the storage tank, must be 10 m above ground level. The solar resource on site averages 4.5 kWh/m²/day at a tilt of 20° from horizontal, orientated toward the equator, which optimizes the solar yield in the worst month. What is the indicative SWP system size?

A: First pass sizing:

1) Key inputs

- $Q = 30 \text{ liters/capita} \times 2,000 \text{ persons} = 60 \text{ m}^3/\text{day}$
- $\text{Design flow} = 60(\text{m}^3/\text{day}) / 7(\text{pumping hours/day}) = 8.5 \text{ m}^3/\text{hour}$
- $\text{TDH} = 100 \text{ m static} + 8.5 \text{ m drawdown} + 10 \text{ m elevation} + 10\% \text{ dynamic losses} = 118.5 \text{ m} \times 110\% = 130 \text{ m}$

2) Total hydraulic energy required = $60 \text{ m}^3/\text{day} \times 130 \text{ m} \times 1,000 \times 9.8 / 3,600,000 = 21.23 \text{ kWh}$

3) Assume that pump motor is optimally sized at its operating point of 60% wire-to-water efficiency

4) Electrical energy required = $21.23 \text{ kWh/day} / 60\% = 35.4 \text{ kWh/day}$

5) Array size required: $35.4 \text{ kW/day} = \text{array kWp} \times 77.4\% \times 4.5 \text{ kWh/m}^2/\text{day}$

Therefore: array size=10.16kWp

- 6) Watertank storage volume should be approximately $120\text{--}180\text{ m}^3$ and is calculated as follows:
 $= Q (\text{m}^3/\text{day}) \times 2\text{--}3 \text{ days} = 120\text{--}180\text{ m}^3$

Costing parameters

SWP system ex-works cost is typically less than \$1.75/Wp (\$1,750/kWp). A 10.18-kWp system would cost about \$18,500. The total installed costs would typically be less than \$3.2/Wp (or \$32,000 in the example). This pricing would apply to larger systems (>10 kWp), or large numbers of small systems. Once-offs in remote locations would naturally attract much higher installation charges. Prices of \$2.2/Wp are likely once large programs are implemented. The price breakdown is more or less as follows:

- PV modules: $< \$0.75/\text{Wp}$ including mounting, for certified modules (\$7,500)
- Pump and controller or power conditioner: \$1.1/kW (\$11,207).
- Balance of system (BOS), cables, etc.: 20%: (\$3,668)
- Installation and related services: 25% (\$5,501)
- Total: (\$27,507)
- Grand total (with profit of 20%): \$32,900
- Not included
 - Borehole and water source development
 - Storage tanks
 - Water reticulation, standpipes, and/or water metering

8.1 What affects SWP performance in real life?

The simplified SWP sizing algorithm presented is adequate for understanding the sizing dynamics, and good for static design conditions. In reality, there are several input variables that are not constant and thus affect SWP performance over the course of a year. Therefore, to be rigorous, sizing algorithms must evaluate the conditions over the course of a whole year to determine when the limiting design conditions occur. Below are some of the key variables:

- *Seasonal changes in solar radiation.* Essentially, SWP water output is more or less proportional to irradiation. First-pass sizing is usually based on average insolation for the year, or perhaps the worst month of the year. It is necessary to assess the output for days when radiation will be less than the annual average, and less than the monthly average. Tilt angle optimization is required.
- *Seasonal changes in pumping head.* Similarly, drops in water levels will affect pump output. Water output is more or less indirectly proportionate to pumping head. Too conservative an estimation of water level will result in system oversizing.
- *Sunny versus cloudy days.* Average insolation is insufficient. A key variable is the amount of cloud cover and intermittency of the sunshine. Especially, variable speed drives coupled with AC pumps tend to suffer degraded performance under stop-start solar conditions, since they require minimum power conditions start-up, and take considerable time to spool up once threshold levels are reached. So, while 2 days might have the same amount of cumulative insolation, a clear morning with zero sun in the afternoon is likely to yield far higher water output than an intermittently cloudy day. Derating for this kind of local variability is important for certain motor pump types in particular.
- *Seasonal changes in water demand.* Experience shows that demand is not constant throughout the year. For human consumption, the variations are low (25%), but for livestock and irrigation the variations can be

significant, up to 80%, with zero demand in very wet seasons. The analysis of these variables can be cumbersome.

8.2 Sizing software

The combinations of variations in seasonal water demand, seasonal solar radiation, and seasonal changes in pumping head make for a considerably more complex optimization, which is best suited for computer-based iterations. Further, while basic sizing can be accomplished on simple spreadsheets, optimizations and **final designs are best done using proven software**, examining actual motor pump sets and their specific operating points. In general, this will be done by suppliers, who must present their predicted system performance with their offers. Examples of some sizing and simulation software:

- COMPASSTM, specific to solar pump manufacturer LorentzTM.
- Grundfos Product CentreTM, specific to pump manufacturer GrundfosTM.
- PVSystTM, which can be used to size and simulate any PV system but requires engineering knowledge of individual components in case of SWP.
- HOMERTM, which can be used to do basic energy balances, without knowledge of the specific components, and performs annual simulations.

9. SYSTEM INSTALLATION AND OPERATIONS AND MANAGEMENT

In a PV system, the “balance of system” or BOS refers to all hardware components other than the main components. In a solar pumping system, the main components are the PV panels, pump, and pump controller, with the BOS comprising the PV array mounting structure, cables/wires, switches, fuses, piping, water meters, data loggers, etc. Installation and related services, on the other hand, include engineering design, transport to site, site preparation, installation services, commissioning, training, and maintenance. The BOS installation and related services can account for 30–50% of total capital costs, and are an important part of setting up a solar pumping system.

9.1 Installation and commissioning

Although a detailed description of equipment installation procedures is outside the scope of this document, key considerations include:

- Inventory of equipment
- Array location and safety
- Safety standards
- Equipment protection standards, including earthing
- General security
- System performance

Array location. Maximized solar energy production depends on panel location and orientation. Panels should be equator-facing, with panel tilt predetermined based on latitude and local weather conditions to maximize incident insolation and facilitate panel cleaning during the rainy season. Shading at any time of day should be avoided. Because many solar pumping systems are located in remote areas, the risk of vandalism and theft can be significant, and panels should not be easily accessible by the public. If the use of trees and vegetation for shielding is deemed acceptable, then adjustment to sizing may be required if this reduces the amount of available solar radiation due to shading, especially in early morning and late afternoon. This should be decided before installation.

Safety standards. PV systems present a unique combination of hazards and risks, which must be addressed by sound design and specifications followed by proper installation, operation, and maintenance of the system. In large pumping systems, high-voltage DC arrays require special cabling, switch gear, and clear

labelling.

Equipment protection. Protecting equipment against faults on both the DC and AC sides requires careful attention to earthing design and protective components. Risk of lightning damage is addressed by grounding (giving electrical lightning surges a direct path to the ground that bypasses valuable equipment) and by installing lightning arrestors and surge protectors.

Another major risk is that of vandalism and theft. Measures to curb this risk include:

- a) Build community ownership.
- b) Locate the solar array in a populated area with regular foot traffic.
- c) Fence the array to make access more difficult.
- d) Arrange for security guards.
- e) Install motion-detecting sensors and alarms whenever possible.
- f) Spot-weld bolts or use tamper-proof bolts, screws, and fasteners.
- g) Use anti-theft array mounting frames. These metallic structures hold the panels and are designed to withstand strong winds. There are three types of frames: ground, roof, and post (see Figure 13).

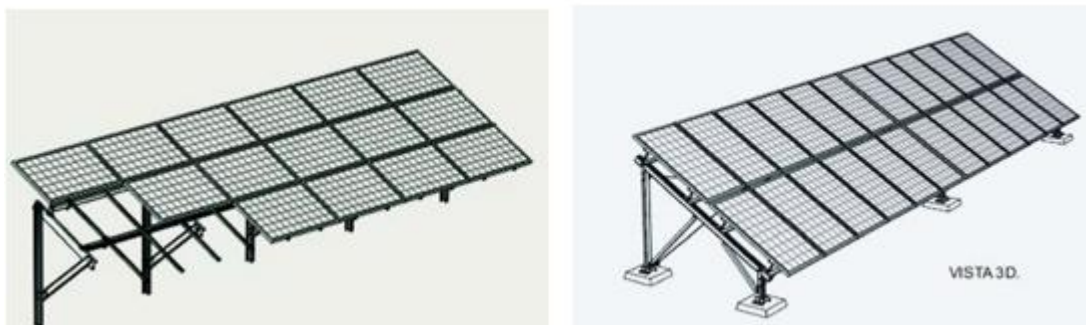


Figure 13. Models for post and ground mounts. Source: Hiasa.

Commissioning immediately follows installation and refers to the process of “handing-over” the system to the client, i.e., ensuring that all system components have been properly installed, are in good condition and that the system is operating as expected. Commissioning comprises three main elements: documentation, inspection, and testing, and should be carried out in accordance with the IEC/BS EN 62446 (for high-voltage DC arrays and earthing). General installation, including the AC side, should be in accordance with IEC 60364-9-1 (low-voltage electrical installations; installation, design and safety requirements for photovoltaic systems), and/or with British Wiring Standards BS 7671. Documentation should include single line diagram, individual component documentation, an O&M manual, and equipment warranty information. Testing benchmarks the system's performance against the design requirements and assumptions, notably by measuring the water output against solar radiation and pumping head (IEC 62253).

9.2 Operation and maintenance

After the system has been installed and commissioned, focus shifts to O&M throughout its lifetime. System operation can be optimized by closely monitoring and recording key system parameters (data logging), enabling operators to assess system performance or demand changes.

One crucial aspect of maintenance is warranties, usually against defective components or poor workmanship. Under the defects period of 1 to 2 years, any items that fail, are not installed to standard, or are damaged by natural calamities must be corrected on site at cost to the contractor/supplier/ installer.

Table 2. Illustrative warranty periods for solar pumping system components.

Component	Usual warranty period
Solar panels	25 years
Pump/motor	2-5 years
Inverter	5-10 years
Remaining components	1-2 years

During the warranty period, the supplier is also expected to check system components and perform preventive maintenance at least quarterly (in any case, neither pumps nor panels require heavy maintenance, with panels only needing periodic cleaning) to attend to user complaints within a reasonable period of time, and to resolve any system breakdowns within 3 days. In addition to component warranties, the supplier may also provide a performance warranty on the system as a whole, ensuring that it will meet or exceed the design performance for a number of years. (See Table 3 for some example warranty time lines.)

Sustainability of solar SWP has been a challenge in many countries and especially in rural areas, with systems failing often within a short time after commissioning due to lack of proper O&M. It is therefore increasingly common for communities to establish comprehensive maintenance contracts with suppliers during warranty periods, and it is a good practice to extend such contracts beyond the warranty period. Suppliers should further secure system sustainability by training system operators, namely on basic plumbing skills useful for repairing leakages in the pipe network and on handling the advanced inverters and sensors common in modern solar pumping systems.

Since solar panels have no moving parts that could be affected by rust or break down, solar power requires very limited maintenance, other than regular dusting. Cleaning the solar panels with water is recommended to remove any dirt or dust.

10. DISCUSSION

This study is based on case studies and success in similar settings where a solar-powered water pumping system has been used as a replacement and had positive outcomes. The approach in this study is to select a PV array that will size the motor pump system, and make the motor start pumping to meet water demand. As a reference to an article from Water Mission (2018), the voltage supplied by the solar array will need to exceed the minimum voltage required by the pump motor, or the pump will not start; and that the voltage from the solar array must not exceed the maximum voltage acceptable to the pump motor, or it will damage the motor. Also reported in Morales and Busch (2010), the panels should exceed the pump's minimum required voltage, but should not exceed the pump's maximum input voltage and current. In this design, the solar output voltage of 18.8 V is rated above the pump's required minimum voltage of 17 V. The output voltage (18.8 V) and output current (17.7 A) from the solar array are rated below the pump's maximum input voltage (50 V) and the pump's maximum input current (18 A). This is quite reliable and trouble-free when properly installed. Table 4 shows the specifications of the components in the designed solar-powered water pumping system; and a price for the whole system can be investigated by contacting different solar water pumping system dealers.

11. CONCLUSION

The design for a PV-powered water pumping system for drip irrigation is presented. The focus is on determining how much water a crop needs daily, and choosing a PV array that will power a water pump to lift water from a well to a storage tank. Water demand for crop irrigation in Karshi was

discovered to be 10,000 L per day for a field size of 1 ha. A good match between the pump and PV module(s) was considered in order to ensure efficient system operation. A pump that has the capacity to supply a flow rate of 2.4 m³/h at a TDH of 14.2 m was selected (a Lorentz PS2-150 C-SJ5-8). After analyzing the pump curves, it was found that the pump motor requires about 258 W of power to achieve the desired performance. After studying the manufacturer's specifications, it was observed that the motor has an input voltage range of 17 to 50 volts DC and a maximum current draw of 18 A. After reviewing various solar panels on the market, a solar panel with the appropriate configuration was chosen (peak power of 50 W, operating voltage of 17.7 V, and operating current of 2.8 A). The power generated by the three 110-watt solar panels wired in parallel effectively powered the submersible pump. The pump delivers approximately 40 L of water per minute from the well to an elevated water storage tank. This designed system can provide a consistent power source for irrigation pumps, enabling farmers to optimise water usage and increase crop yields. Therefore, it is suggested that a pilot be run in Karshi to see if it works and then scale up to the rest of Nigeria.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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ANALYSIS AND EVALUATION OF PHOTOVOLTAIC SOLAR WATER PUMPING SYSTEMS AS A SUSTAINABLE APPROACH TO IMPROVE WATER UTILISATION EFFICIENCY

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ABSTRACT

Present paper aims to discuss scope and limitations of photovoltaic solar water pumping system. Components and functioning of PV solar pumping system are described. In addition, review of research works of previous noteworthy researchers has also been done. Irrigation is well established procedure on many farms in world and is practiced on various levels around the world. It allows diversification of crops, while increasing crop yields. However, typical irrigation systems consume a great amount of conventional energy through the use of electric motors and generators powered by fuel. Photovoltaic energy can find many applications in agriculture, providing electrical energy in various cases, particularly in areas without an electric grid. In this paper the description of reviews on a photovoltaic irrigation system, is presented. Since various irrigation points of organization are located in areas without an electric grid, photovoltaic cells can provide the necessary power for the operation of this automatic irrigation system. To further enhance the daily pumping rates tracking arrays can be implemented. This system demonstrates the feasibility and application of using solar PV to provide energy for the pumping requirements for sprinkler irrigation.

1. INTRODUCTION

Diesel-powered pumps are widely employed in farming and grassland irrigation. However, there can be problems of reliability and availability where fuel supply is erratic and expensive, high maintenance cost, and short life expectancy. These and recent concerns for the environment associated with the diesel engines call for a viable alternative source of power for irrigational water pumping. Renewable energy sources have gained a lot of attention as a replacement for fossil fuels or as a supplement in hybrid systems. Solar-powered (photovoltaic)

systems are one of the viable alternatives that have attracted considerable attention in this regard. They have been deployed in many remote regions for various applications, ranging from rural electrification and community water supplies to irrigation and livestock water supplies. Although photovoltaic (PV) systems generally have a high investment cost, it has many features which make it attractive as an alternative source of power for water pumping. It is clean, as it produces no carbon emission, it generates no noise, and it has low operational and maintenance cost. This manuscript presents a detailed intensive review of solar-powered water pumping systems as reported in the literature to serve as a quick reference to researchers and engineers who are working or interested in the subject.

Photovoltaic water pumping system is one of the best alternative methods for irrigation. The variation of spatial and temporal distribution of available water for irrigation makes significant demand on water conservation techniques. Hence solar powered Automated Irrigation System provides a sustainable solution to enhance water use efficiency in the agricultural fields using renewable energy system removes workmanship that is needed for flooding irrigation. Environmental pollution is prevented with renewable energy and energy production from local resources is encouraged. The use of this photo-irrigation system will be able to contribute to the socio-economic development. It is the proposed solution for the present energy crisis for the Nigerian farmers. This system conserves electricity by reducing the usage of grid power and conserves water by reducing water losses. Proposed system is easy to implement and environment friendly solution for irrigating fields. The system was found to be successful when implemented for bore holes as they pump over the whole day. Solar pumps also offer clean solutions with no danger of borehole contamination. The system requires minimal maintenance and attention as they are self-starting. Solar energy is the most abundant source of energy in the world. Solar power is not only an answer to today's energy crisis but also an environmental friendly form of energy. Photovoltaic generation is an efficient approach for using the solar energy. Solar panels (an array of photovoltaic cells) are now a day extensively used for running street lights, for powering water heaters and to meet domestic loads. The cost of solar panels has been constantly decreasing which encourages its usage in various sectors. One of the applications of this technology is used in irrigation systems for farming. Solar powered irrigation system can be a suitable alternative for farmers in the present state of energy crisis in India. This is green way for energy production which provides free energy once an initial investment is made (Harishankar et al., 2014).

Nowadays, as the increasing shortage of water resources, promote water saving irrigation technology and has become the inevitable choice to fill the water crisis. Today the generation is heading towards ultra-technologies. Water pumping has a long history; so many methods have been developed to pump water. People have used a variety of power sources, namely human energy, animal power, hydro power, wind, solar and fuels such a diesel for small generators.

The most common pumps used in remote communities are:

- Hand pumps
- Direct drive diesel driven borehole pumps
- Electric submersible pumps with diesel generator
- Solar submersible pumps

2. LITERATURE REVIEW

Photovoltaic (PV) technology generates power from solar radiation. Numerous efforts have been undertaken to assess, monitor, and enhance the performance of various components of a

photovoltaic (PV) system: a PV module (Abdallah, 2004; Vick and Clark, 2004; Huang and Sun, 2007; Hansen et al., 2000; Lorenzo, 1994), a controller (Hohm and Ropp, 2003), a battery (Copetti et al., 1993; Gergaud et al., 2003; Achaibou et al., 2012), a pump (Vick and Clark, 2011), and a pump motor (Bhat et al., 1987). Such research have been beneficial in enhancing the efficiency of photovoltaic system components. Nonetheless, various parameters must be evaluated for optimal photovoltaic system design to ensure the needed reliability in a certain area. This entails a comprehensive examination of all interacting physical (plant and soil types, irrigation system specifications, PV system dimensions, site characteristics), meteorological (solar radiation, air temperature, relative humidity, wind velocity, precipitation), and managerial (irrigation scheduling) variables to attain the desired reliability of the PV system. A technique that integrates the characteristics of the centre pivot irrigation system, daily crop water requirements, soil moisture conditions, irrigation applications, photovoltaic array output, load demands, and energy storage is essential for assessing the reliability of a solar-powered centre pivot irrigation system. This comprehensive method could significantly enhance the system's effective sizing. External environmental variables will adversely affect photovoltaic performance. Key factors to consider include insolation, ambient temperature, and wind speed (Van Dyk et al., 2005).

The configuration of a photovoltaic system is highly adaptable. The optimal use of solar energy occurs when the panels are directly linked to the load. The efficacy of water pumping is partially attributed to the removal of the intermediary phase, specifically the battery bank, for energy storage. A direct connection between the photovoltaic array and the pump enables water to be pumped during daylight hours. The most efficient direct-connect systems involve pumping water to an elevated storage tank, wherein electrical energy from the panels is transformed into the potential energy of the elevated water, available for on-demand usage, typically by gravity (Hamidat et al., 2003). The whole efficiency, from sunshine to water flow, has been documented to surpass 3% (Daud and Mahmoud, 2005; Pulfrey et al., 1987).

This method is a straightforward and environmentally sustainable alternative for irrigating land. The technique proved effective when used to boreholes, as they operate continuously throughout the day. Solar pumps provide a clean solution without the risk of borehole contamination. The system demands minimum maintenance and oversight, as it is self-starting. To optimise the monitoring of daily pumping rates, arrays can be employed. This system illustrates the viability and implementation of solar photovoltaic technology to fulfil the energy demands for pumps in sprinkler irrigation. Despite the substantial capital expenditure necessary for the implementation of this system, the overall advantages are significant, rendering it economically viable in the long term (Harishankar et al., 2014).

Economic analysis indicates that photovoltaic pumping systems for irrigation in Bangladesh are more viable than diesel engine pumping systems. From an economic perspective, the cost of a photovoltaic (PV) pumping system for a single season of irrigation is somewhat greater than that of a diesel engine pumping system, attributable to the elevated expenses associated with PV modules and their components (Haque 2001). The automation of an irrigation system will significantly diminish the disparity between energy requirements and consumption, consequently conserving resources and minimising waste. The primary benefit of this initiative is the optimisation of power consumption via water resource management, as well as the conservation of the government's subsidised electricity. This demonstrates an efficient and economical method of irrigation that will automate the agricultural sector (Yalla et al., 2013).

In Nigeria, establishing a grid system is typically prohibitively costly due to the considerable distance of rural settlements from existing grid lines. Although fuel is accessible domestically, the transportation of that fuel to isolated rural areas can pose significant challenges. Numerous isolated settlements lack roads and related infrastructure. Renewable energy is advantageous for water pumping applications in distant regions of numerous developing nations. The transportation of renewable energy systems, such as photovoltaic (PV) pumps, is considerably more straightforward than that of other types, as they can be disassembled and reassembled on-site (Khatib, 2010). The life cycle cost analysis conducted on both systems demonstrates that the photovoltaic water pumping system is the more cost-effective option compared to the diesel water pumping system (Narale et al., 2013).

Cuadros et al. (2004) assert that this method was appropriate for assessing the dimensions and consequently the viability of solar-powered irrigation systems, given the substantial expense associated with photovoltaic (PV) systems. The feasibility is assessed not only in terms of the cost of photovoltaic systems but also regarding the land area necessary for implementation. Glasnovic and Margeta (2009) examined the maximum regions that might be economically watered. Kelley et al. (2010) indicated that photovoltaic irrigation was both technically and economically viable, contingent upon the availability of sufficient acreage for the solar array. A primary difficulty regarding solar panel utilisation for power generation is the quantity of panels needed and the space they would occupy. In agriculture, this is particularly significant as it directly affects the land available for cultivation. This study demonstrated that only a minimal percentage of the two-acre plot would be necessary for the panels. This illustrates the viability and implementation of solar photovoltaic systems to meet the energy demands for drip irrigation pumping.

Several factors were considered to determine the pumping requirements and, consequently, the solar panel area, including the selected crop, the dimensions of the planting area, the number of peak sunlight hours, the efficiency of the solar array and its electronics, the elevation for pumping, and the efficiency of the pump. Consequently, these considerations would influence the viability of such systems. This study demonstrated promising outcomes regarding the spatial requirements for solar panels utilised to generate power for the drip irrigation of hot peppers on a two-acre plot (Persad 2011). Particular studies have examined the application of photovoltaic systems on small farms (Roul, 2007), whereas prior feasibility analyses assessed either the economic or technical viability of photovoltaic irrigation. The majority of the investigations were unique to system size and location. Research examining systems with power demands about 1 kW has been performed in Namibia, Jordan, and India (Mahmoud, 1990; NAMREP, 2006; Meah et al., 2008). The majority of the literature indicates that photovoltaic irrigation is theoretically viable for diminutive systems of one acre in size (Kelley et al., 2010). Solar pumps have been a topic of discussion in India for some time. A 2005 estimate by Purohit and Michealova indicated that approximately 7,000 were already operational in the field. Nevertheless, solar-powered tube wells currently utilised by farmers are difficult to locate. As the cost of photovoltaic (PV) cells continues to decline in accordance with Moore's Law, while diesel prices escalate, solar-powered pumping has become a financially viable concept.

Water pumping has historically been the most dependable and cost-effective application of solar-electric (photovoltaic, or PV) systems. Most photovoltaic systems depend on battery storage to power lights and other appliances at nighttime or when sunlight is unavailable. Most photovoltaic pumping systems operate without batteries, as the photovoltaic modules directly power the pump. The photovoltaic pumping system is exceedingly straightforward in the

absence of batteries. It comprises three components: the solar array, a pump controller, and the pump. The sole component in motion is the pump. The solar modules are guaranteed to generate power for 20 to 25 years. The anticipated lifespan of the majority of controllers is 5 to 10 years. Pump lifespan can range from 5 to over 10 years, with many built for field repairs. Maintenance often necessitates cleaning the solar modules every 2 to 4 weeks, provided the pump or controller does not malfunction. This task can evidently be performed inexpensively by unskilled local labour (Aligah 2011). Recently, Hammad (1999) conducted a study on the utilisation of photovoltaic-generated electricity for pumping water from 13 wells located in the eastern and southeastern desert, distant from the national grid, as well as in the southern regions of Jordan, characterised by complex topography. These pumps can independently deliver 40–100 m³ of water per day to satisfy the daily requirements of residents in those regions. A fully automated irrigation system has been conceived, constructed, and tested with solar photovoltaic cells and a digital controller. The system is cost-effective, dependable, mobile, and compact. Reductions in electricity and water costs can substantiate the initial expenditure, which may exceed that of conventional systems, over time. It inflicts minimal harm on the environment and alleviates the public utility of an additional burden. It is applicable in both small and large farms, gardens, parks, and lawns. It can also function as a universal solar-based controller for managing building doors, water heaters and air conditioning systems (Ali 2001).

Solar water-pumping technology is commercially available, has an established track record of reliability, requires minimal specialised staff during operation, and incurs low and cheap operation and maintenance costs. Photovoltaic pumps offer numerous advantages, including their operation on freely accessible sunshine, resulting in no fuel or electrical expenses. They are environmentally sustainable, dependable, and possess an extended operational lifespan (Yingdong 2011). The benefit of utilising solar energy for water pumping is that substantial volumes of water are needed during daylight hours, coinciding with peak solar intensity, when photovoltaic panels generate optimal energy and, consequently, water output. These solar pumps can be put in areas that are not linked to the national power grid (Ahmet 2012).

Photovoltaic systems for groundwater pumping are utilised in Upper Egypt, demonstrating that the cost per unit of water pushed by these systems is considerably lower than that of diesel systems (Yingdong 2011). In India, 9 million diesel-powered pump sets for irrigation operate out of a total of 21 million pump sets, each with a capacity of 3.73 KW (5 HP). Of the 9 million diesel pump sets, 75% are expected to be located in solar resource regions, resulting in a total of 6.75 million diesel pump sets in these areas. Of the 6.75 million diesel pumps, 70% possess land suitable for the installation of photovoltaic (PV) systems; hence, the total number of pump sets in solar resource regions with land available for solar PV installation amounts to 4.725 million, equating to 16,785 MW, which is only half of the diesel pumps. The substitution of 4.5 million diesel pumps conserves 223.8 billion litres of diesel and reduces carbon dioxide emissions by 469.98 billion kilogrammes annually (Arora 2013). The aforementioned procedures indicate that the optimal nominal electric power of the PV generator, based on reference parameters in the Arilje region, with a decade average daily water requirement of 12.8 m³ ha⁻¹ day⁻¹, would adequately meet the irrigation needs of raspberries throughout the entire observed period (Gajic et al., 2013). At an annual operation of 2000 hours, Claro Energy's 8.5 kW solar pumps, priced at Rs. 1 million, will conserve approximately 17,000 kWh of power annually, valued at Rs. 85,000 per year (Mukherji, 2007).

3. SOLAR ENERGY

The energy from the sun can be converted directly in the form of heat or converted into electrical energy and then utilized. Accordingly, the solar energy is classified into

solar thermal and solar photovoltaic (PV). Solar PV can be considered the only form of electricity that can be generated anytime and anywhere provided sunshine is available. Two types Solar photovoltaic (PV), Solar thermal/ The earth receives more energy from the sun in just one hour than the world uses in a whole year. Photovoltaic (PV) Technology is a process of generating electrical energy from solar radiation. The principle of conversion of solar energy into electrical energy is based on the effect called photovoltaic effect. Solar thermal has multiple applications like water heating, drying vegetables and agricultural products, cooking, etc. Solar energy has been applied to various areas including Water heating, Drying of vegetables, Agricultural drying and water pumping for households and for agricultural purposes.

3. PHOTOVOLTAIC CELLS

Photovoltaic cells are devices which 'collect the light and convert it into electricity. The cells are wired in series, sealed between sheets of glass or plastic, and supported inside a metal frame. These frames are called solar modules or panels. They are used to power a variety of applications ranging from calculators and wrist-watches to complete home systems and large power plants. PV cells are made of thin silicon wafers; a semi-conducting material similar to that used in computer chips. When sunlight is absorbed by these materials, the solar energy knocks electrons loose from their atoms, allowing the electrons to flow through the material to produce electricity. This process of converting light (photons) to electricity (voltage) is called the "photovoltaic effect".

4. PHOTOVOLTAIC APPLICATIONS

Solar panels are used in a variety of applications. The applications vary from small simple lanterns to large elaborate power plants.

- Rural and urban households for domestic purposes like lighting.
- Communities, small industries and institutions like schools, for lighting as well as for powering television sets, computers, etc.
- Water pumping systems.
- Telecommunications, as these systems are often installed in isolated places with no other access to power.
- Health center vaccine refrigeration in rural areas. Such solar refrigerators are also utilized to store blood plasma. WHO supports programmers that install solar power for medical purposes

5. SYSTEM COMPONENTS

The whole system of solar pumping includes the panels, support structure with tracking mechanism, electronic parts for regulation, cables, pipes and the pump itself.

5.1 Solar Panels or Modules

Solar panels are the main components used for driving the solar pump. Several solar panels connected together in arrays produce DC electricity, interconnections are made using series or parallel combinations to achieve desired voltage and power for the pump.

5.2 Solar Pump

Centrifugal or submersible pumps are connected directly to the solar array using DC power produced by the solar panels. Solar pumps are available in several capacities depending upon the requirement of water.

5.3 Support Structure and Tracking Mechanism

Support structure provides stability to the mounted solar panels and protects them from theft or natural calamities. To obtain maximum output of water, a manual tracking device is fixed to the support structure. Tracking increases the output of water by allowing the panels to face the sun as it moves across the sky.

5.4 Foundations (Array and Pump)

Foundations are provided for support structures and pump.

5.5 Electrical Interconnections

A set of cables of appropriate size, junction boxes, connectors and switches are provided along with the installation.

5.6 Earthing Kit

Earthing kit is provided for safety in case of lightning or short circuit.

5.7 Plumbing

Pipes and fittings required to connect the pump come as part of the installation.

6. FUNCTIONING OF PV SOLAR PUMP SYSTEM

A 50-watt photovoltaic solar panel can power a 12-volt pump, which can move 1,300–2,600 liters per hour (or 350– 700 gallons). Standard plastic fittings and half-inch piping connect these elements to a water saving tank of 500–1,000 liters. A sturdy stand should be built for the water tank to provide gravity flow, and a frame should also be constructed to provide the best angle for the solar panels. Multiple filters are needed to protect the life of the pump and minimize clogging in sprinkler emitters and tubes. A solar pump combined with affordable drip irrigation kits can be used with a wide variety of high-value crops to increase water efficiency, minimize fertilizer loss, and irrigate hilly terrains.

6.1 Key Aspects of PV Pumping System

In general, the investment required for a PV pumping system is Rs 250-300/Wp (where Rs is the Indian rupee and Wp is watts peak). For example, the cost of a 900 Wp unit would be Rs 225,000-270,000, but with subsidies, this will be reduced to Rs 50,000. To make the best use of solar energy, the PV system, the groundwater pump and the water distribution system have to be well matched. The PV power provided must cover the power demand of the pump adequately. This is determined by the relationship between the required discharge flow, the total head and the pump efficiency. This depends on the type of pump, which in turn depends on the depth of the available water source. Although positive displacement pumps are preferred for large heads, centrifugal pumps are most commonly used. Photovoltaic (PV) panel electrical outputs are rated according to industry Standard Test Conditions (STC) of 1000 W m^{-2} incident solar radiation at an operating cell temperature of 25°C and under an absolute air mass of 1.5. Environmental conditions met outside the laboratory will cause a decrease in PV performance from the STC rating, the magnitude of which depends on the module technology. Many additional losses are incurred due to the inefficiencies in transferring energy from the PV panels to a load, such as a pump or battery bank, thus resulting in a secondary decline of performance. Though there have been studies measuring outdoor performance of PV modules, there is a great need for further field studies of complete PV systems.

Another important aspect would be the ability to model the potential solar radiation, PV power

output, and subsequent water output for the purpose of irrigation scheduling. Photovoltaic powered water pumping systems (photo-irrigation) have been studied by researchers in many years. Studies mostly concentrated on DC motors cause of energy obtained from solar panel is DC (Lawrance et al., 1995, Dursun et al., 2005). These are shown that better results were obtained for performance analysis (Kolhe et al., 2004., Kolhe et al., 2000). Photo-irrigation system has advantages than flooding irrigation. Some of these are, bringing utilization of water sources more efficient, preventing erosion and growing of weeds only by irrigating the requested areas (Cuadros et al., 2004), decreasing moisture stress (Pande, et al., 2003), no operation cost, providing opportunity for local energy sources and exhibiting a parallel point of view with water requirement (Ghoneim, 2006). In terms of automation, developed wireless technologies, researches focused on automatic irrigation with sensors in agricultural systems (Kim 2009, Stone, et al., 1985, Zhang 2004). In this connection, research works of some other noteworthy researchers Alyu and Sambo (1989), Bajpai et al. (1991), Maurya et al. (2013), Maurya et al. (2013; 2014), Okanta et al. (2003; 2004a; 2004b) and Porsoki (1996) are worth mentioning. The advantages of using wireless sensor is to reduce wiring and piping costs, and easier to install and maintenance especially large areas (Dursun et al., 2010). Energy of pumps used for the agricultural irrigation is generally provided from electrical energy or fossil fuels. Since fossil fuels commence to annihilate besides its increasing of prices and hazards to environment alternative energy seeking efforts has become inevitable also in agricultural sector. Solar energy that is sensitive to environment, clean and requiring no maintenance is an alternative renewable energy source especially for countries like Turkey having a high amount of annual solar irradiation rate. When it is considered by means of requirement for irrigation the advantage of PV pumping systems is that water demand and increasing for sun shining are compatible characteristically (Anis et al., 1994). In summer months obtained solar energy increases and also naturally water requirement of trees increases.

The cost of solar PV has come down and cost of diesel has been regularly increasing. At present the cost of solar PV is very much less to diesel, solar PV cost shall be half of diesel within three to four years, since approaching towards grid parity. 400,000 telecom towers are associated with diesel generating sets having capacity 3 to 5 KW. 60% Telecom towers located in urban and semi urban areas and 100% located in the villages are run by diesel generating sets. Recently in 2013, Maurya et al. (2014) focused their attention to capital cost modeling. In fact, off-grid potential is unlimited in India and is about 20 to 25% potential of the world (Arora, 2014). Solar water pumps are often thought of as being an expensive technology, which is not able to pump enough water and which is not durable. However, solar water pumps have come a long way in 25 years and today there are solar pumps on the market which have improved on previous technology, e.g.: Submersible pumps which can pump up to 200m heads; Pumps that are able to pump larger volumes of water, e.g.: At 100m, about 10,000 litres per day; At 50m, about 20,000 litres per day; Above performance can be doubled through dual systems (if the borehole allows this).

- Low maintenance requirements (3 to 5 years);
- Good performance which means fewer solar panels to pump the same amount of water;
- Some of the pump models can be backed-up by a genset to pump additional water with the same pump during the night or during overcast days;
- Good quality and reliability
- Simple to install

Furthermore, solar pumps are well known for having the following features:

- Require minimal attention as they are self-starting;
- Solar pumps are “good” for boreholes as they pump over the whole day;

- Weak boreholes can be used effectively with a low volume pump due to pumping 8 to 10 hours a day;
- In most cases, a solar pump offers an ideal solution to the diesel option which requires operating funds (with uncertainty about future diesel prices), time investment for operating pump (manual starting etc.) and logistics for fuel, maintenance, installation and de-installation;
- Tracking arrays can be used to increase daily water pumping rates;
- Solar pumps offer clean solutions with no danger of borehole contamination.

6.1 Solar Water Pumping Systems

The Solar Pumping System harnesses the abundantly available solar energy to power the pumps to draw water from water bodies. The longer life span gives an edge to promote use of this system. The principal means of water lifting in the developing world are presently the hand pump for smaller demands and the diesel or electric-driven pump for larger quantities. Solar PV pumping can be more appropriate than these technologies in many applications. Spare parts and fuel can be difficult or expensive to obtain, and the quality of fuel is often poor due to adulteration, which leads to frequent maintenance requirements. Solar water pumps are cost-effective in the long run and dependable method for drawing water. It is a highly effective and smarter solution in situations where electric supply is unreliable or unavailable; or fuel cost & maintenance costs are considerably high. A solar pump is often the best option for reducing the cost and labor which is required in arranging the diesel.

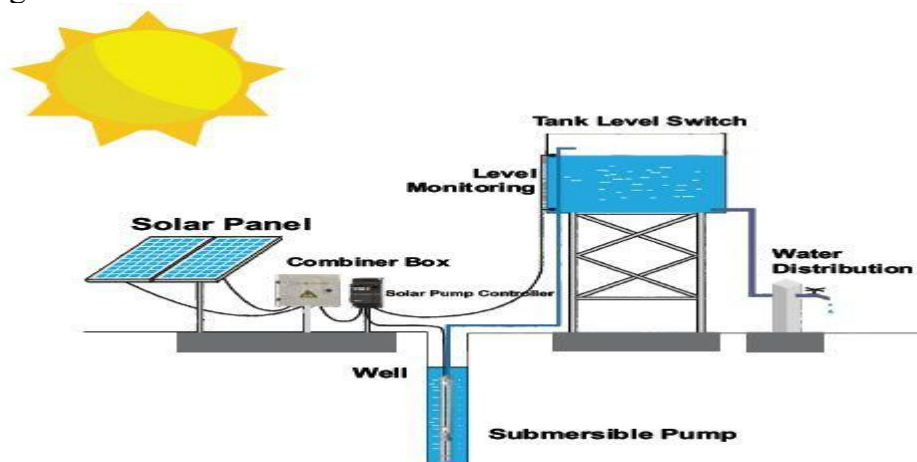


Figure 1. Diagrammatic representation of solar pumping water system

6.2 Applications of Solar Pumps

The potential applications of solar pumps include:

- Irrigation (individual farmers or cooperatives)
- Portable water supply for Institutions (traditional niche market for schools and health clinics)
- Community-scale watersupply schemes (larger village schemes)
- Livestock water supply (individual or communal)

Water pumped for irrigation can be used as drinking water also if it is free from impurities and is potable. Therefore, PV systems for irrigation and drinking water will be described together. Access to a safe and clean water supply is one of the primary factors in

improving the health and quality of life in rural communities. In the developing world, especially in Africa, Asia, and Latin America a lot of people do not have the option of using clean water for drinking. These remote regions are not connected to a centralized system for supplying drinking water.

A water pump does not necessarily require batteries. To save costs, the majority of solar powered water pumps can run directly from the solar panels. Electricity aimed at running the water pump is not stored in batteries, but the water is instead stored in a water tank or pond. This way the water is stored and can be used anytime required.

In terms of automation, developed wireless technologies, researches focused on automatic irrigation with sensors in agricultural systems. The advantages of using wireless sensor is to reduce wiring and piping costs, and easier to install and maintenance especially large areas.

6.3 Efficiency

The solar pump efficiency as we know is the ratio of output vs input and if represented in percentage it is known as percentage efficiency. In the case of a solar pump, the overall efficiency can be split into three parts

- The efficiency of conversion of solar energy into electrical energy.
- The efficiency of the motor drives the pump.
- The efficiency of a pump or the pumping efficiency.

A very narrow band in solar energy spectrum gets converted into electrical energy, Therefore the efficiency of conversion is very low of order of 12 to 20% which mainly depends upon the design of the solar panel and the ambient conditions like temperature, etc. The motor efficiency is of the order of 80 to 90% again mainly dependent upon the design and rating of the motor. Finally, we come to pump efficiency which normally is of the order of 50 to 65%. Adding up all the three efficiencies we come to the overall efficiency of 47 to 58%.

6.4 Area Required and Lifespan of SWP

The area required by the solar pump depends on its size. For every 1 HP of the solar pump size, the area required is 100 square feet. Therefore, a 2 HP solar pump required about 200 square feet area to be installed and 5 HP solar pump requires about 500 square feet area. Relocation of a solar pump is not advisable. The minimum lifespan of solar panel is 25 years. Lifetime of pump is 10-15 years. The Pump, solar modules and pump controller have a warranty for 5 years.

6.5 Advantages and Limitations

One of the major milestones in solar water pumping is the elimination of dependency on an external power source. The solar panels in the pumping system coalesce solar irradiation to provide the electricity required to pump up groundwater from beneath the ground. With a surge in the means of production, the prices of solar water pumps have gone down favorably for users in recent years. This has propelled users to recover their investments faster and use the pump for free water harvesting for a longer period of time.

Nevertheless, solar water pumps are a one-time investment opportunity with guaranteed rich dividends in store. One of the major factors why it is promoted on large

scale Nigeria is because it significantly reduces the financial burden of electricity distribution companies who provide subsidized power to its agriculture consumers.

The limitations of solar pumps and their corresponding solutions are presented in Table 1.

Table 1. Limitations of solar pumps

Limitations	Solutions
High initial investment cost	Government subsidies and easy bank finances are available through bank of Agriculture though bureaucracy processes sometimes hamper the process
Output fluctuation due to varying solar isolation (weather dependent)	Use of VFD and battery can ensure a constant supply without voltage fluctuations Grid connected solar pumps use grid energy to run the pump when solar energy is not available
Vandalism and theft	and pump controller Bank insurance is available at minimum premium
Excessive groundwater extraction because operators face near zero marginal-cost of pumping groundwater	Creation of groundwater recharging structures and judicious use of solar pumps

The advantages of solar pumps are:

- Operation is independent of grid power and reduces dependency on electric grid;
- Negligible maintenance cost;
- Highly cost-effective in long run against diesel and electric;
- Environment Friendly - No Carbon emissions;
- No fuel cost - uses available free sunlight;
- Helps to increase in agricultural productivity due to consistent water supply;
- Ease of operation as it is highly automatic;
- Solar pumping systems are modular so can be tailored to current power needs;
- Properly installed solar systems are safe and low risk due to low system voltage;
- Reduces the electricity distribution companies' (DISCOM) financial burden in long term even after providing subsidized pump sets to farmers;
- Solar pumping systems are modular so can be tailored to current power needs and easily expanded by adding PV panels and accessories.

6.6 Revolution of Solar Pumps over last decade

Solar water pumping systems capacity and ability have expanded. New pump and motor designs have increased water outputs over the entire pump range.

Prices of photovoltaic (PV) panels have dropped exponentially: High demand for PV modules for grid tied applications has resulted in massive economies of scale in production as well as competition among vendors. The commodity price of silicon, the key material, has also dropped substantially

The number of SWP manufacturers and suppliers has increased: Old monopolies have been broken, and although the technology leaders continue to innovate, competition is fierce on price, performance, and quality. SWP is being mainstreamed and awareness is

growing: Further opportunities are rising as intensive awareness campaigns support and elaborate on the details of system performance and savings. The investment costs associated with buying solar water pumps has come down in the past few years.

However, the factors which influence the deployment of a solar water pump are numerous and include:

- Economic viability
- Access to capital subsidy
- Standardization and quality control of products and service
- Water management
- Environmental regulation at local level

Considering these factors, we can say that solar water pumping can provide significant environmental and socio-economic benefits at the local and national levels. At the local level, the technology can present a reliable source of energy in remote areas, especially areas that are not connected to the electricity grid or lacking a regular supply of costly liquid fuels. On a national level, solar water pumping can help stabilize, increase and diversify agricultural production and stabilize the electricity grid.

Many governments and institutions have realized that Solar Water Pumping can act as a catalyst to increase farmers' income and is an extremely viable way to expand energy access across developing countries and communities. Additionally, this creates a strong resistance to changes in rainfall patterns. This is the reason many governments have opted to subsidize the cost of solar pumping, increasing the pool of shared learning for this emerging technology.

6.7 Components of the Solar Pumping System

A Solar pumping system consists mainly of Solar Panels, Motor-pump set and a Controller, interconnected cables, earthing rod and lightning arrester. Sometimes a water storage tank is also provided depending upon the requirement. This chapter describes in more detail the major components used in solar pumping systems.

7. SOLAR PV CELLS AND SOLAR ARRAY

7.1 Solar Cells

The smallest part of the device that converts solar energy into electrical energy is called a solar cell. Solar cells are in fact large area semiconductor diodes, which are made by combining silicon material with different impurities. Sand, a base material for semiconductors, is the most abundantly available raw material in the world. The ordinary sand (SiO_2) is the raw form of silicone.

All photovoltaic (PV) cells consist of two or more thin layers of semiconducting material, most commonly silicon. When the semiconductor is exposed to light, electrical charges are generated and these charges are conducted away by metal contacts as Direct Current (DC). The electrical output from a single cell is small, so multiple cells are connected together to form a 'string', which produces a higher direct current.

Power generated by a solar cell depends on its efficiency. The power generated per unit area is usually in the range of $10 \text{ milliWatt/cm}^2$ to $25 \text{ milliWatt/cm}^2$ which corresponds

to 10% to 25% cell efficiency. The maximum area of a single, typical wafer based solar cell is $15 \times 15 = 225 \text{ cm}^2$; with 15% efficiency peak power generated by the solar cells would be $225 \text{ cm}^2 \times 15 \text{ milliWatt/cm}^2 = 3.37 \text{ Watt}$.

Nowadays solar panels with efficiency of over 18% are also commercially available.

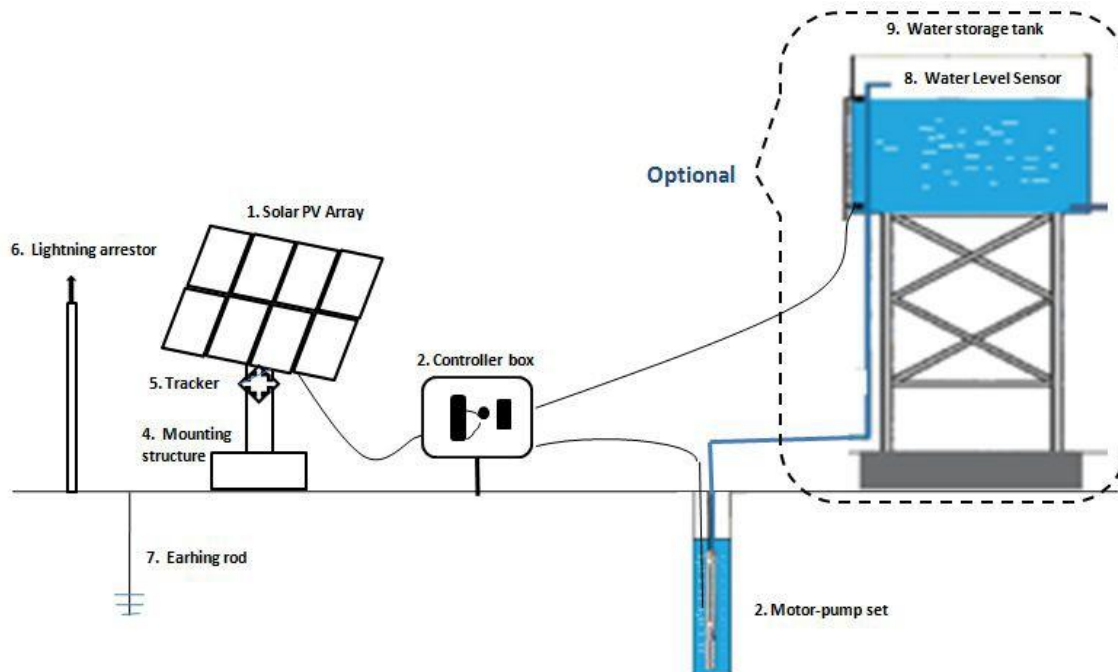


Figure 8. Solar-powered borehole system

7.2 Solar PV modules

It is not solar cells alone, but PV modules that are installed in the field to supply the power. Solar PV modules are made of solar cells by connecting many cells in series and/or parallel. The solar PV modules are encapsulated properly so that they can work in outdoor conditions for a very long period of time. The module power output depends on the power output of individual cells. By choosing appropriately sized cells, modules of given power rating can be obtained. The power output of the module depends on the condition under which module is working (radiation, temperature, etc). Solar PV Modules can be considered as a big solar cell (array of several solar cells connected in series and parallel) with larger voltage and current output than a single solar cell.

In the first level of interconnection to increase the power output, cells are connected to form solar PV modules. These days solar PV modules are available with power ratings ranging from 3 Watts to 400 Watts. In the second level of interconnection solar PV modules are connected together in the form of an array to get the power which is more than a single PV module power output. A PV array can provide us with power ranging from few Watts to several megawatts.

Higher power can be obtained using low power solar cells by making series and parallel connections of cells. Series connection is done in order to increase the output voltage while parallel connection is done in order to increase the current output. While making a series and parallel connection of cells it is assumed that all cells have the same

characteristics, i.e. they are identical in all aspects like size, material and efficiency.

PV modules are rated according to their power output, based on a solar irradiance of $1,000 \text{ W/m}^2$ at a specified module temperature. Panel output data includes the peak power (maximum power generated by the panel referred to as watt-peak or Wp), voltage (volts or V), and current (amps or A). In addition to irradiance, PV module temperature affects the amount of power produced, with higher temperatures decreasing power output.

The main global standard for crystalline silicon modules is IEC 61215, which, like similar standards, is awarded largely based on tests administered to samples of modules produced. Since modules cannot be tested throughout their 25-year lifetime, accelerated stress testing is performed. One of the main tests is the verification of the nominal peak power that a PV module can deliver under standard testing conditions (STC), which include 1 kW/m^2 of solar irradiation perpendicular to the panels and 25°C of PV cell temperature.

Quality of solar modules, and matching of solar module performance is especially important in solar pumping systems consisting of large arrays of modules connected in series, where array performance, hence system performance, depends on the performance of the weakest module. Even one module with inferior output can have a devastating effect.

7.3 Classification of Solar Panels

Solar panels are broadly classified based on solar cell technology which is being used. The ways in which interconnection of solar cells is obtained in the thin film technology and in a wafer-based technology (Crystalline) are different. In thin film technology, cells are interconnected during the process of manufacturing of solar cells. While in wafer-based technology solar cells are manufactured first and then interconnected to make PV modules.

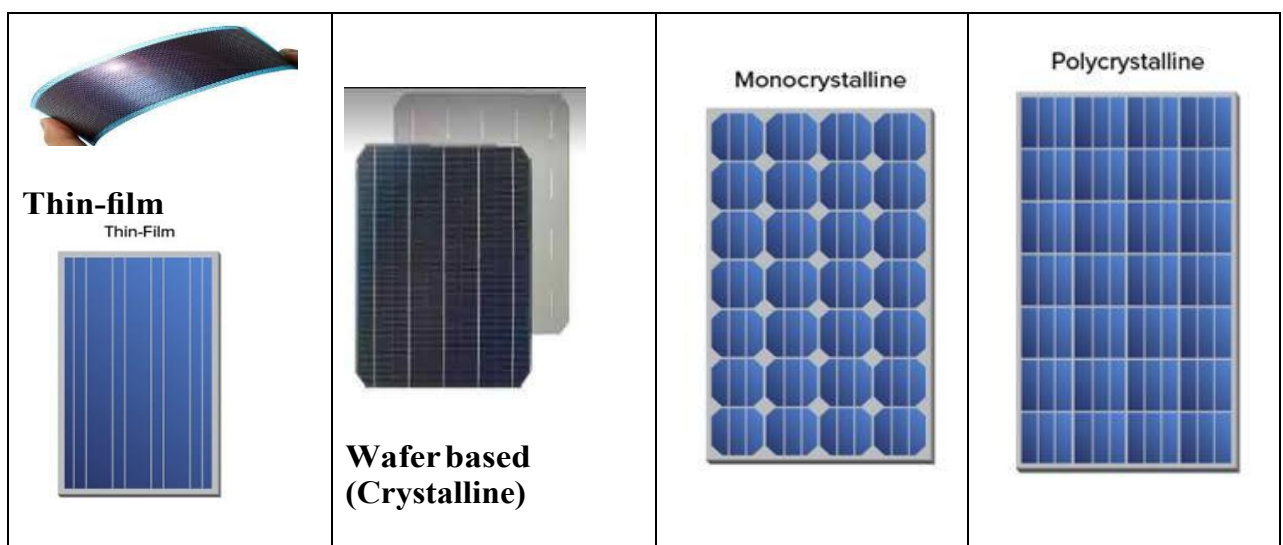


Figure 9. Types of solar panels

7.3.1 Monocrystalline silicon PV panels

These panels are made using cells sliced from a single cylindrical crystal of silicon. This

is the most efficient photovoltaic technology, typically converting around 15% of the sun's energy into electricity. The manufacturing process required to produce monocrystalline silicon is complicated, resulting in slightly higher costs than other technologies.\

7.3.2 Polycrystalline silicon PV panels

Also sometimes known as multicrystalline cells, polycrystalline silicon cells are made from cells cut from an ingot of melted and recrystallised silicon. The ingots are then saw-cut into very thin wafers and assembled into complete cells. They are generally cheaper to produce than monocrystalline cells, due to the simpler manufacturing process, but they tend to be slightly less efficient, with average efficiencies of around 12%.

7.3.3 Thin-film based solar panels

It basically uses less silicon, hence named thin film. It tends to be less expensive but also has lower efficiency than crystalline modules. A thin-film solar cell is a second generation solar cell that is made by depositing one or more thin layers, or thin film (TF) of photovoltaic material on a substrate, such as glass, plastic or metal. The advantages and disadvantages of each type of solar panels are presented in Table 2.

Table 2. advantages and disadvantages of each type of solar panels

Type	Advantage	Disadvantage
Monocrystalline	• Highest efficiency (upto 22%) • Takes lesser space • Higher durability • More efficient in warm weather	Higher Cost
Polycrystalline	• Relatively easier to make • Cost-effective as compared to Monocrystalline panels • Higher temperature coefficient, therefore impact of temperature on power output is less	Efficiency of panels is around 15%
Thin-film based solar panels	• Mass production is easier • High temperature and shading have lesser impact on power output	• Lowest space efficiency • Faster degradation as compare to mono & poly panels

7.4 Solar PV system

Harnessing power from the sun, the PV system consists of a systematic arrangement of components designed to supply usable electric power for a variety of applications. Photovoltaic power capacity is measured in watts peak (Wp). When the PV modules are exposed to sunlight, they generate direct current (DC). An inverter then converts the DC into alternating current (AC). A small PV system has capability to power a single home or even an isolated AC or DC based device. Many cells make a module. Many modules make an array. This is demonstrated in Figure 1.

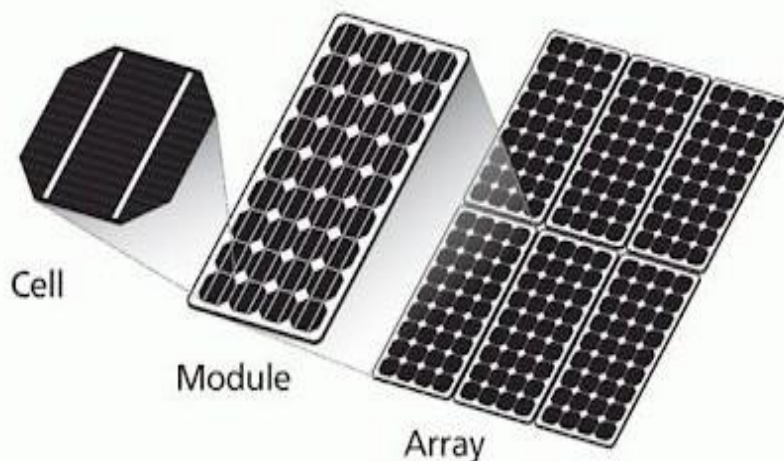


Figure 10. From cell to array

Solar PV systems can be classified based on the end-use application of the technology. There are two main types of solar PV systems:

- Grid-connected (or grid-tied) solar PV systems
- Off grid (or stand-alone) solar PV systems

Off-grid solar PV systems are applicable for areas without a utility grid. Currently, such solar PV systems are usually installed at isolated sites where the power grid is far away, such as rural areas or off-shore islands. But they may also be installed within the city in situations where it is inconvenient or too costly to tap electricity from the utility grid.

7.5 Module Mounting Structures

Various module mounting structure solutions are available as per requirement of site / project / customer. They are designed in order to maximize yield within a minimum area. Tailor made structures are also available to suit project requirements, which maximize the generation from solar modules. Most commonly used are Galvanized Iron structures which can withstand wind speed up to 150 kmph or as per requirement of site. Aluminium structures are also seen, however they are not as strong as GI structures. Structure designed to facilitate replacement of modules if required.

Common theft-prevention measures include:

- use of lock tie nuts
- spraying the owner's ID with non removable spray paint onto the back of the panels;
- integrating the solar panels into the mounting structure (non detachable)
- placing the mounting structure out of easy reach by using elevated structures, fences or floating PV systems.

There are two basic types of mounting structures

- Ground mounted structures which can be single pole mounting or multiple leg mounted structures
- Rooftop mounting structures. These are installed where ground space is not available
- Apart from this, floating structures are also noted in various location where land area is inadequate

Additionally, tracker based mounting structures are installed that rotate the solar

modules in the direction of maximum solar irradiation

7.6 Common Features of Module Mounting Structure

Irrespective of various MMS designs, certain components are common in all designs. They are:

- There will be legs driven into the ground usually concreted to support the weight of the entire mounting structure. They are called column posts
- There will be rafters which are tilted at an angle suitable to utilize solar power in the most optimal manner as per design. Usually, the tilt is facing the equator at an angle equal to the latitude.

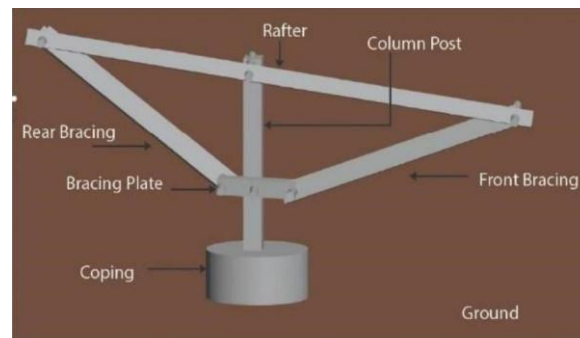


Figure 11. Load Carrying Components of Module Mounting Structure - Column and Rafter

- Rafter will be connected to column post either directly or using Front and Rear bracings with cleats
- There will be purlins placed on the rafter perpendicular to it. Based on the number of rows of modules, the number of purlins required are decided. Modules are placed over the purlins and clamped to the purlins
- Long Bracings - These are supporting GI arms provided for strength and stability of the structure at various places.

MMS are specified by the number of rows and columns. 4×3 MMS means there are 4 modules in a row and 3 such rows

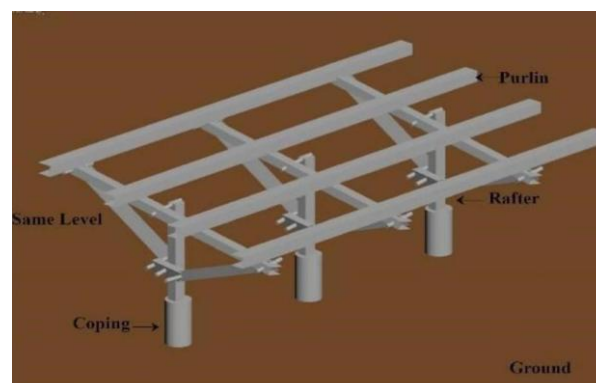


Figure 12. Purlin over rafter for module housing

Ground mounted structure 	Ground-mounted array can be positioned for best exposure to sunlight. This option requires a suitable ground area and type of soil, however. Typically, ground-mounted arrays get high exposure to sun, and they are a comparatively cheap option. The main advantage of this structure is ease of installation. Also it is easier to clean the panels.

Pole-mounted structure 	This is one of the most popular installation methods for solar PV power in areas where ground- or roof-mounting is not suitable is to mount the array on poles. To increase the number of panels, more poles shall be created adjacent to the solar pump. Installing a pole-mounted solar PV array is a more detailed operation than other forms of mounting, and the structural loading on a pole-mounted array must be determined in advance. Every manufacturer has different designs and sizes available.

Roof Mounted structure 	A roof-mounted array can be installed on a suitable existing structure (such as a shed). This is the standard mounting option for urban grid-connected solar PV systems. The size of the array that's possible is limited by the available installation area on the roof. This is not very popular in solar pumping systems, but can save cost of mounting structures, if the roof is readily available adjacent to the solar pump. Again, cleaning of panels can become challenging if access to the roof is difficult.

Overhead Tank structure 	This is popularly used in drinking water applications where the fewer number of solar panels are available. Storage tank is to be mounted on height to create water pressure. Existing structure of overhead tanks can be utilized to support the panels, this reduces the space requirement. But it becomes challenging to clean the solar panels.

The fixed installation of solar panels on a rigid structure is the cheapest, most reliable and most common method. Metal supports that are pile-driven into the ground are generally recommended for larger systems. They make the utilization of concrete foundations redundant and save labor and material cost. However, in developing

countries, simple concrete foundations are often used for smaller installations and represent an appropriate solution, provided that static requirements are met.



Fixed Tilt single column MMS

A single supporting column concreted to the ground holds the entire MMS. Hence the rafters need to be supported like a grid from beneath and the entire rafter grid will have to be fastened to the column post.



Seasonal Tilt single column MMS

In seasonal tilt the only difference is that instead of fastening the rafter grid to column post, a semi-circular GI plate with holes are provided to fasten the rafter at multiple angles



Fixed Tilt multi column MMS

In multi-column MMS there is one column leg to support each rafter (or two column legs to support each rafter if the number of rows are higher). Since legs support individual rafters, rafters need not be interconnected as a grid. Purlins can be placed perpendicular to the rafters over it.



Seasonal tilt multi column MMS

In each rafter the seasonal tilt option is provided with a GI semi-circular plate with holes for specific angles.

7.7 Single Axis Tracker

These rotate the array in the east-west axis only, following the sun at a fixed angle of elevation from the time it rises in the east until it sets in the west. Installing a single-axis tracker for your solar PV array results in higher power output in the mornings and evenings. Decision to install tracker is purely economic based on the trade-off of additional energy available Vs cost of tracker.

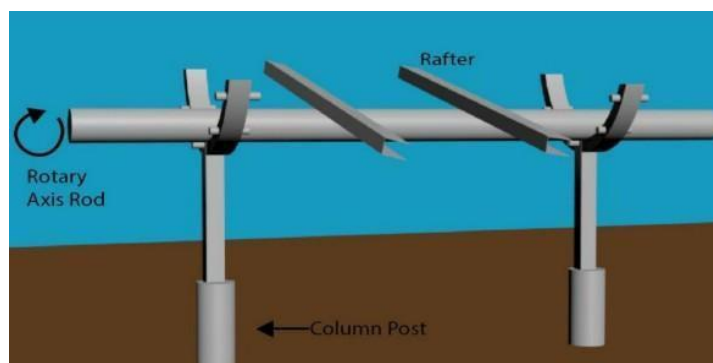


Figure 11. single axis mechanisms

7.8 Double Axis Tracker

These rotate the array on an east-west axis and also can tilt it on a second axis in south-north direction, so that it is angled directly towards the sun at all parts of the day. The strength of dual-axis trackers is their ability to maximize energy production. A motor controlled by a programmed microcontroller, which actuates a pneumatic actuator that can move the entire rafter-purlin grid mounted on a single column, in both axes.

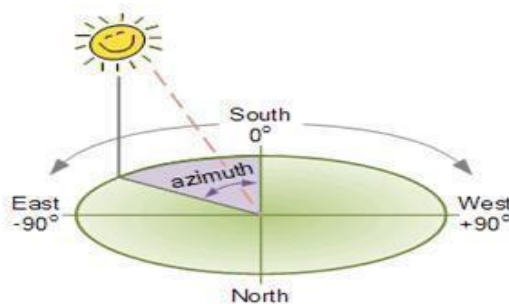
Since they have a higher degree of mechanical complexity, they are expensive and require more maintenance during their lifetime. Hence, they are seldom used in Solar pump installations.



Figure12. Mounting Mechanism

7.9 Azimuth Angle

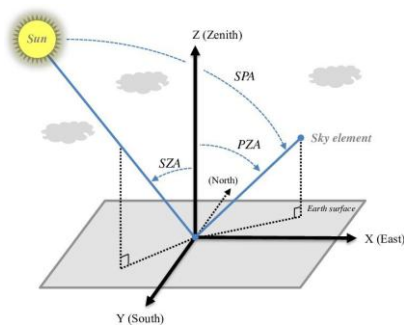
The angle between true south and the point on the horizon directly below the sun. Azimuth angle of the solar module is an indicator of alignment of the module with respect to (true) south. For modules facing (true) south this angle is 0° and for module facing (true) north this angle is $\pm 180^\circ$.



The sun's apparent location east and west of true south is called azimuth, which is measured in degrees in east or west of true south. Since there are 360° and 24 hours, sun appears to move 15° in azimuth each hour. When the sun is true south in the sky at 0 degrees azimuth, it will be at its highest altitude for that day. This time is called solar noon. On fall and spring equinoxes, the sun rises at the due east of south and sets at the due west of south. Whereas in winter months it rises at the south of true east and sets at the south of true west; in summer months it appears to rise north of true east and set north of true west. In winter, the sun appears to be at its lowest in the southern sky. So, they must be tilted up from horizontal at an angle 15° greater than the latitude. Conversely, if a PV system is going to be used mostly in summer, where the sun will be highest in the southern sky, it may be most advantageous to optimize the performance of the panel by tilting it 15° less than the latitude.

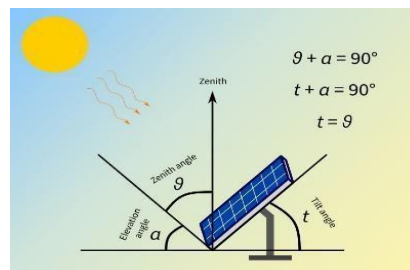
7.10 Zenith Angle

Zenith Angle is the angle between the sun's rays and the vertical. The Zenith angle is calculated based on the angle of incidence of the sun with the perpendicular line from the round surface. The zenith angle varies throughout the day.



7.11 Tilt Angle

Tilt Angle is also known as Elevation Angle is the angle between the horizontal ground and the solar panel. As the sun changes its position every hour due to the rotation of earth, there is no exact direction towards which the panels can always be faced. So, the system design should be in such a way that solar collection is optimised by positioning the array to take full advantage of the maximum amount of sunlight available at a particular region.

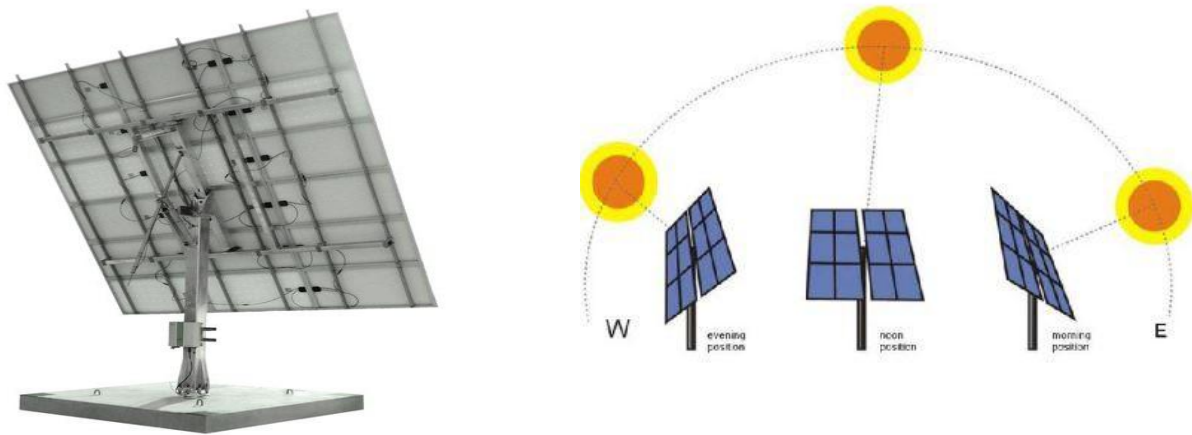


The panels need to be facing south since the installation is being done in the northern hemisphere. In case of the southern hemisphere, the solar modules should be installed facing the north direction.

Due to the rotation of earth about the tilted axis, the sun appears at different altitudes above the horizon at solar-noon throughout the year. The latitude of the location tells us about the altitude at which the sun appears above the horizon. When the tilt angle or the angle at which the panels are elevated is equal to latitude, the insolation is optimized. In the northern hemisphere, the sun travels towards the southern sky. In Nigeria, the tilt angle usually varies between 10° to 17° , based on the latitude of the installation location.

7.12 Trackers for solar panels (Optional component)

A solar tracker is a device that orients solar panels toward the Sun. Trackers are used to minimize the angle of incidence between the sunlight and a solar panel. The purpose of a tracking mechanism is to follow the Sun as it moves across the sky. The amount of solar energy available for collection from the direct beam is the amount of light intercepted by the panel. Or to put it in another way, the energy intercepted is equivalent to the area of the panel surface which receives perpendicular direct beams of sunlight.



7.13 Motor-Pump Set

Water pumps are driven by electrical motors, which convert electrical energy (produced, in the case of solar pumps, by PV panels) into mechanical energy. It can be said that the pump is the heart of the Solar Pumping system. Primarily they are classified based on their placement (underwater and above the water). These pumps are surface and submersible pumps. These pumps can be further classified into categories depending upon the type of motor used in the pump. Most motors typically run on either direct current (DC), where the electrical flow does not switch direction periodically in the wires; or alternating current (AC), where it does. In solar pumping systems it is advisable to use the term 'Motor-Pump set' instead of calling it only pump or motor.

Based on various applications and parameters appropriate motor pump sets can be selected for the solar pumping system. But before studying these combinations it is important to understand the concepts which broadly classify the pumps and motors to avoid any confusion.

7.14 Submersible Pumps

A solar submersible pump is located deep below the ground level; whenever the suction head is beyond a depth of 10 metres. In a region where the water table keeps on dipping radically, installation of the submersible pump within the water table in a bore well is more practical. The pump remains submerged under the water.

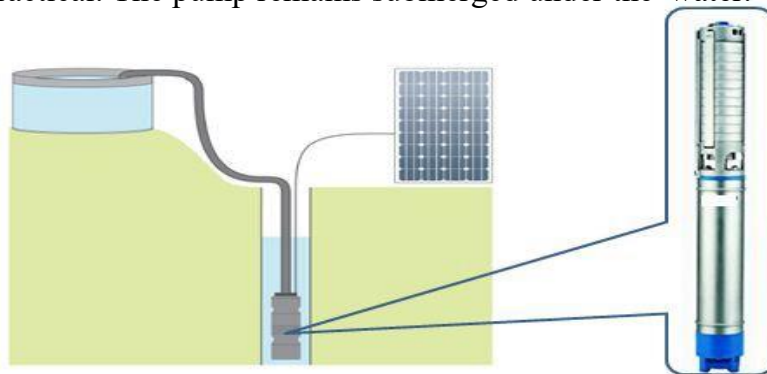


Figure 3. Submersible Pump

The installation of a submersible pump often requires that a bore-well is dug which can be

a costly undertaking but without which the water cannot be taken out. Sometimes, a submersible pump can also be located inside water bodies like lakes, canals, etc. Submersible pumps as their name portrays, are completely submerged in the water source. One important thing is the efficiency of submersible pumps as water pressure naturally forces water into a submerged pump rather than utilizing energy to do so. Being submerged all the time, submersible pumps do not require manual priming, which can easily become a very time-consuming chore. Surface mounted pumps are also known to be much louder, and since it is on the surface, it just looks out of place. When the pump is immersed into the water, air won't be available around the motor to provide cooling. Therefore, oil and water are used as coolants.

7.15 Oil filled Motors

Oil is served as a coolant in oil filled motors. Oil filled submersible pumps are mostly used in water lifting in wells, irrigation in farmland, hills, residential etc. These can be very advantageous if used in cool areas as oil cannot be frozen. They also have better lubricating conditions and give long service life. These are to be avoided where the quality of water pumped is important, as the oil may leak sometimes.

7.16 Water Filled Motors

Water filled motors use water as cooling material and is mostly used in industrial, residential, farming etc. Water leaks do not pollute the water source and can be fixed for operating beneath the water. The service life of water filled pumps is shorter than oil filled pumps.

7.17 Components of Submersible Pumps

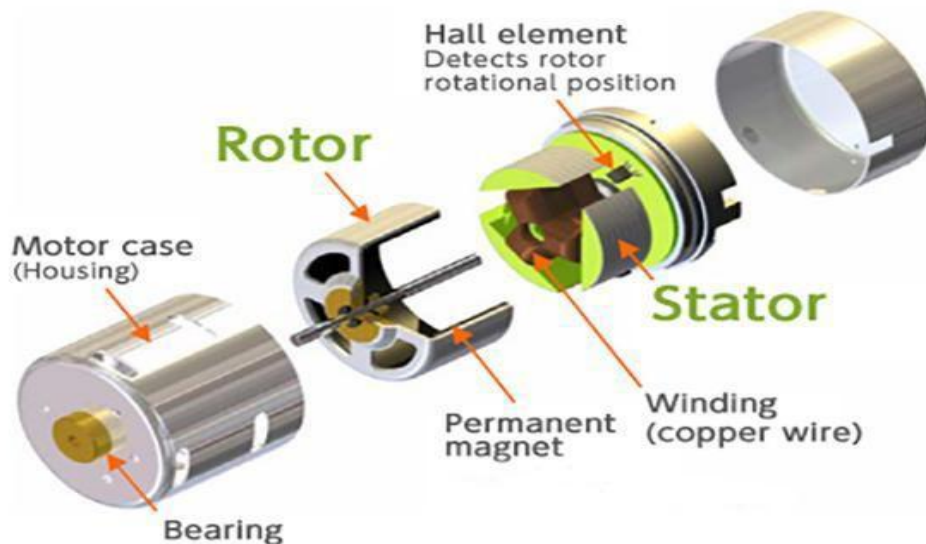


Figure 4. Parts of a Submersible Pumps

The space between the rotor magnets and stator magnets is called the *air gap*. The air gap is an annular space to permit the magnetic lines of force to transmit back and forth between the rotor and stator. The air gap is maintained on both ends of the rotor by an inboard bearing and outboard bearing.

7.17.1. Bearings

The function of the bearing is to reduce friction between the moving parts and allow

smoother rotation, reducing the energy consumption. Submersible pumps use thrust bearings instead of ball and roller bearings. There are no moving parts within the bearing, so if the motor is controlled correctly there are fewer risks of parts failure. They transmit the rotating shaft's axial load to the frame of the motor.

7.17.2. Seals

Mechanical seals improve the efficiency of submersible pumps. In a submersible pump, the motor is hermetically sealed and close-coupled onto the pump body. It protects the bearings and the motor with a vertical shaft that is submerged in the pumped liquid. Water and oil seals are also used for submersible pumps.

7.17.3. Impellers

An impeller is a rotating iron or steel disc with vanes that transfer energy from the motor that drives the pump to the fluid being pumped by accelerating the fluid radially outwards from the centre of rotation. Submersible pumps are multistage pumps, where a series of impellers are connected to the rotating shaft which is driven by the motor.

The water is pulled in through the intake, and as it enters the eye of the impeller, they are thrown out due to the action due to centrifugal force. As a result, water gains both kinetic and pressure energy. The water is carried to the next impeller efficiently with the help of a stationary device called a diffuser, connected right next to the impeller. The diffuser deflects the impeller water and makes it ready for the next impeller stage. This series connection of impellers multiplies the pressure. This is why submersible pumps can pump water to greater heights.

7.18 Surface Pumps

A surface pump is located in the open by the side of a water source, for example an open well, lake or canal. The pump remains out of the water, and generally the motor and the pump can be seen separately. Surface pumps are usually easy to install and maintain.

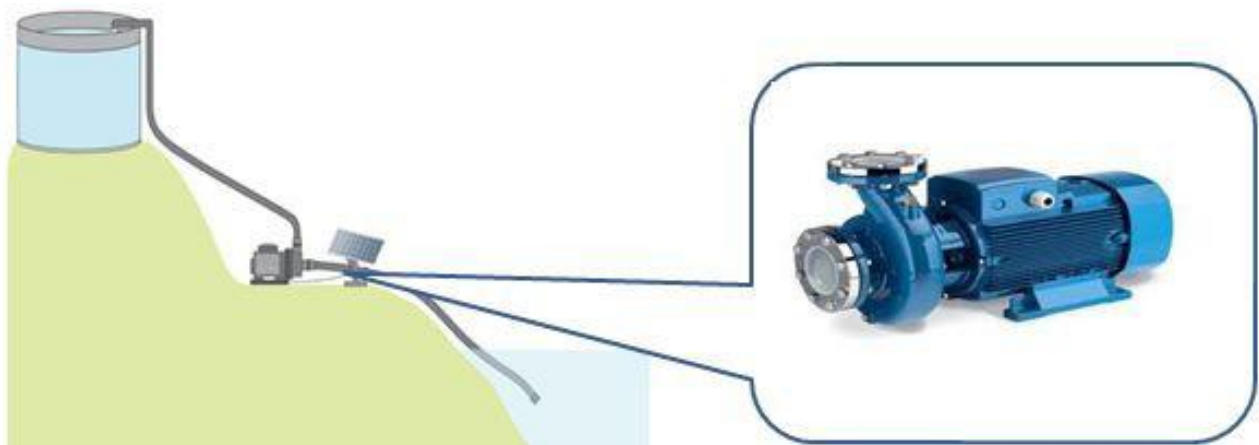


Figure 4. Pictural of a surface ;pump

Surface pumps can also be feasible options in cases where the water table is within a depth of up to 10 meters and an open well is available. These pumps are not they're not situated in the water, meaning they are very easily accessible if anything were to fail or need replacing. The pumps are usually contained within a pump housing to protect them from the elements. The pumps have filter baskets and an inspection cover. Solar water pumping

is becoming increasingly relevant in many applications, especially for livestock watering, drip irrigation, remote houses and where water is needed but no AC power is available. Pumping from remote bores or dams can become very expensive using generators, and the cost of running power lines is sometimes not feasible. In such situations, solar power is ideal comparing to diesel generators.

Surface pumps Allows easy access to the pump itself, but because of the environment, they may require access more often. Winter storms can really affect the productivity and results of a surface pump because it is not below the freezing line, which can cause trapped water to expand inside the pump which could lead to several problems like freezing.

A disadvantage is that Flash floods, wildlife, and thunderstorms can also be a great risk because surface mounted pumps are not as shielded from their surroundings, unlike submersible pumps.

Another disadvantage is the amount of energy surface pumps use; the water must first be moved up out of a water source by a suction force before it can actually reach the pump, this process requires a lot more power than an apparatus that already has the water readily available.

7.19 Components of Surface Pumps

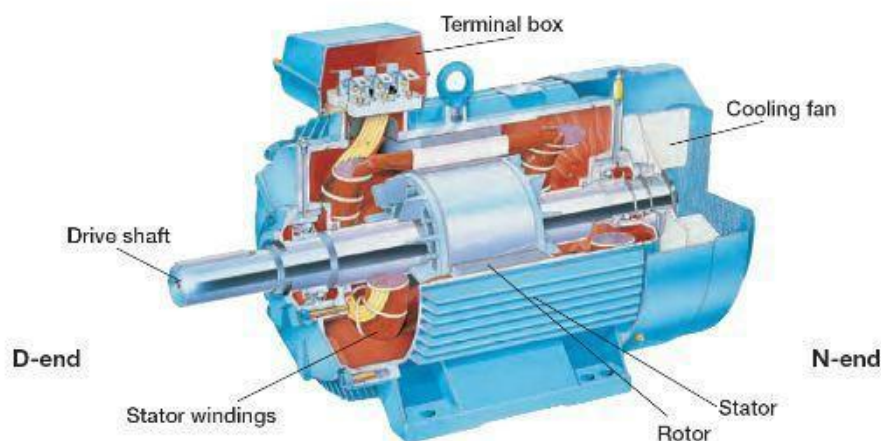
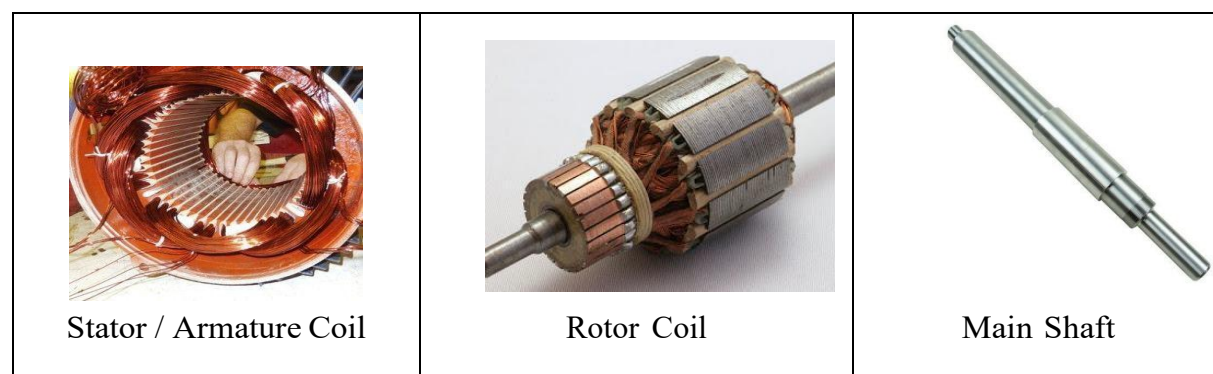
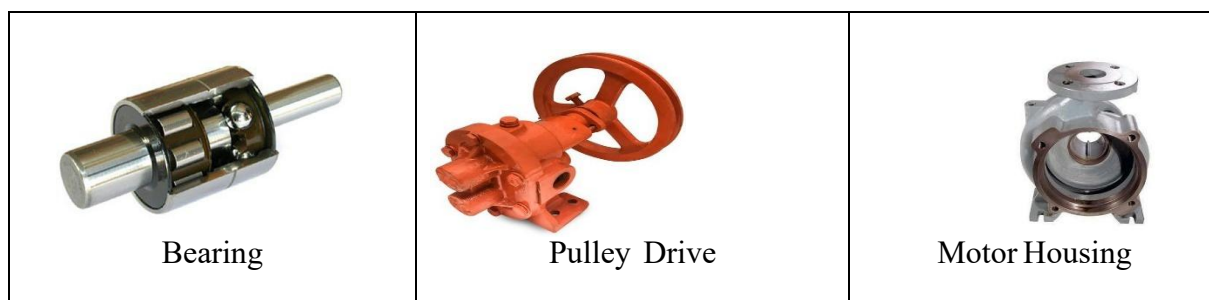


Figure 5. Parts of a Surface Pump





9.19.1. Stator / Armature Coil

The stator is composed of iron plates wrapped by copper winding located around the main axis. This copper is connected to a current source. The function of the stator is to generate a magnetic field around the rotor. When the current is passed through the winding, a magnetic force is induced in the stator. A motor generally has three stator coils. The more the number of coils, the greater the magnetism generated, and faster the pump rotates and faster water is pumped out. For simple electric motors, the stator is replaced using a permanent magnet.

9.19.2. Rotor Coil

Rotor resembles a stator, except that the rotor is a dynamic copper wire as the coil is attached with the main shaft or main axle of the motor that will rotate. The more the number of turns on the rotor the greater the resulting spin. Commonly, a chopper with a small diameter. It aims to make the number of windings more even if it requires a large wire length. The wound end will be connected to another rotor located at the end of the main shaft.

9.19.3. Main Shaft

The main shaft is a rust-proof, durable and temperature resistant aluminium rod that extends to provide attachment for the rotor coil and a drive pulley.

9.19.4. Brush

A copper brush connects the current source with a coil rotor. This brush is attached to a small rotor located at the end of the main shaft. The flow of current is maintained in the same direction using the brushes, even though the rotor rotates, thus the rotation is synchronous and continuous. The structure is supported by a spring located behind the copper brush, which ensures it always hits the brush even when spinning at high speed. A simple electric motor should be equipped with two brushes. The brushes need to be checked regularly for wear and tear, and replaced during servicing if required.

9.19.5. Bearing

The function of the bearing is to produce rotation. A bearing between the shaft surface and the motor housing reduces friction and ensures free movement. Bearings are generally made from aluminum, which has less friction and does not inhibit motor rotation.

6 . Pulley Drive

The pulley drive is located at the outer end of the main shaft, and transfers motor rotation to other components. This acts like a gear, conducting the rotation through the pump.

9.19.6. Motor Housing

The electric motor is covered by an iron plate that protects the parts of the electric

motor. In addition, motor housing also controls the trembling effect of the motor which is rotating at very high speed.

10. Classification of pump-motor set based on current

10.1 AC Pumps and Motors

An AC pump has a motor which operates on alternating current (AC). Direct current generated by solar panels or batteries is converted to AC by an inverter-cum-controller, and is then passed on to the AC pump motor. The conversion from DC to AC leads to small losses in power between the points of generation and consumption.

10.1.1 Advantages

- Low upfront cost compared to DC pumps.
- Easy to set up, installation and availability of maintenance and repair services locally.

10.1.2 Disadvantages

- Low efficiency and water output compared with a DC pump.
- Additional inverter is required.

An AC electric motor is a type of electric motor operating with an alternating current (AC) voltage source. This AC electric motor can be distinguished by its resources as follows:

- Synchronous motor, is an AC motor working at a fixed speed at a certain frequency system. This motor has a low initial torque, and therefore synchronous motors are suitable for low-load initial use, such as air compressors, frequency changes and motor generators. Synchronous motors are able to improve the system power factor, so it is often used on systems that use a lot of electricity.
- Induction motor is an AC powered motor that works based on induction magnetic material between rotor and stator.

10.2 DC Pumps and Motors

A DC Pump has a motor which operates on direct current (DC). Solar Panels generate DC current, which is then passed on to the DC pump motor through a controller. Since the current from solar panels or batteries is directly used, and no conversion to AC is required, there is no/little loss of power between generation and consumption. However, it should be noted that the current should not have to travel a long distance before being fed to the pump in order to minimize the losses.

10.2.1 Advantages

- Approximately 10% higher water discharge as compared to an AC pump.
- No need for an inverter between the solar PV panels and the pump

10.2.2 Disadvantages

- High upfront costs.
- Lack of repair and maintenance services in rural and remote locations.

Direct current electric motor is a type of electric motor that operates with a direct current DC voltage source (DC). DC motors can be distinguished again based on the following resources:

- Separately Excited Motor is a type of DC motor where the field current source is supplied from a separate source other than the electric motor coil, so the DC electric motor is called a separate DC power source (separately excited).
- Self-Excited motor is a type of DC motor where the field current source is supplied from the same source as the electric motor coil, so the DC electric motor is called a self-excited DC power motor.

DC motors are appealing for solar pumping because PV modules producing direct current can be directly coupled to the motor with limited power conditioning. This makes them an economical option for systems with low water demand and a short cable distance between the PV panel array and the motor. For long-distance cabling, however, low-voltage DC motors are not suitable because of power loss in the cable. AC motors can be used in larger solar pumping systems, although they require a DC/AC inverter.

The most suitable pump and motor type for any situation should be determined based on manufacturers' catalogues and motor pump manuals, and specifically on pump/motor pair performance curves (characterized to the IEC 62253 standard) to ensure that the pump/motor pair can deliver the required flow against the total dynamic head

11. STANDALONE (Off-GRID) AND GRID-CONNECTED (ON-GRID) SOLAR PUMPS

Standalone pumps are not connected to the main electrical grid, and the pump completely runs on the energy harnessed from the solar panels connected to the pump. A battery might be used to store the energy generated and pump out the water when sunlight is not available.

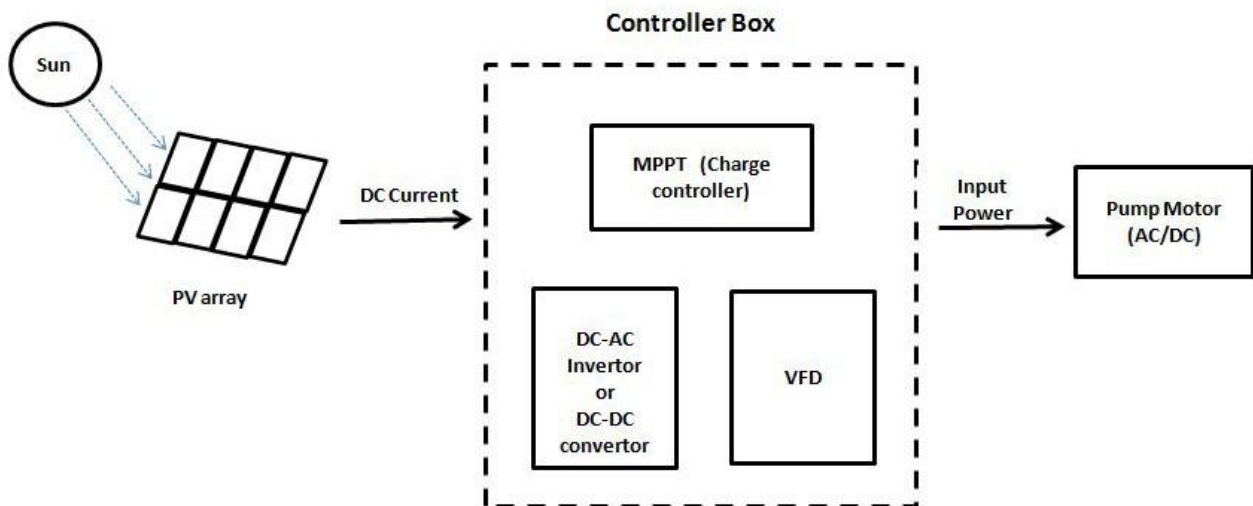
Grid connected solar pumps are becoming popular gradually. Here, the pump can switch its source of power from solar energy to grid connected electricity in the absence of sunlight. Also, excess energy produced by the solar panels during the day can be directed to the grid, which is sold and acts as a source of extra income for the pump owners.

11.1 Pump Controller

Solar pump controller is a device installed between the panels and the pump that allows the solar pump to regulate the intermittent sunshine to provide desired output. The controller box contains the pump controller as well as various electronic components, which provide electronic protection against dry run operation, over and under voltage, short circuit and reverse polarity. The electronics normally include an inverter, power conditioner or pump controller, controls/protections and water sensors.

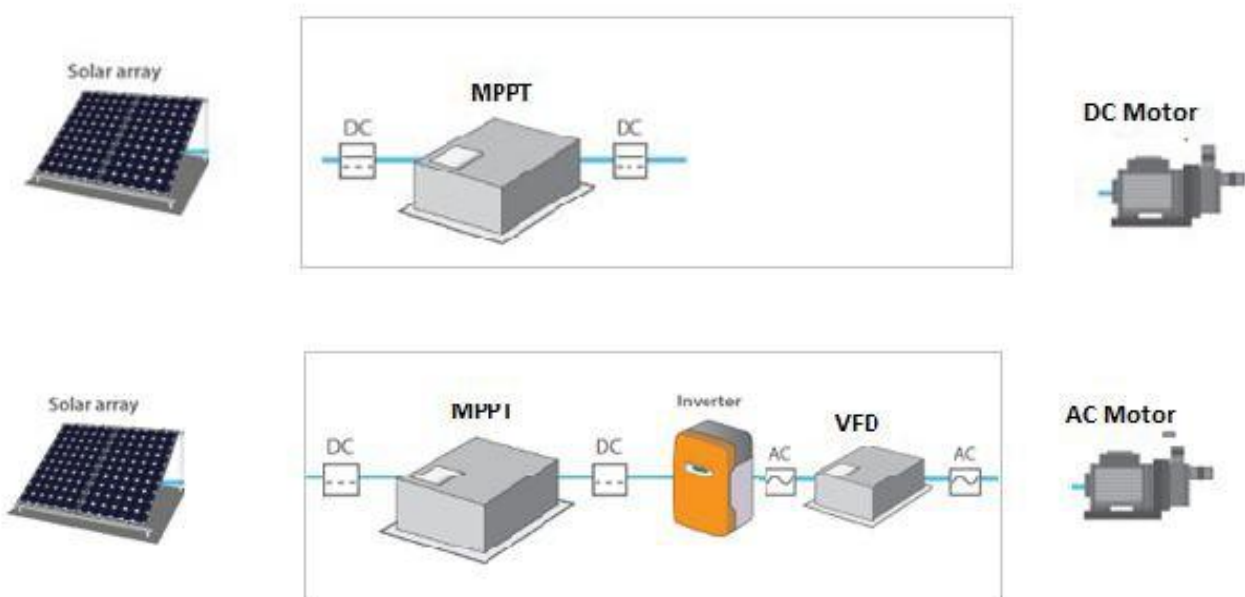
The main functions of the pump controller are:

1. to match the output power that the pump receives with the input power available from the solar panels.
2. to protect the pump against various faults which may damage the pump, thus increase its lifetime and reduce the need for maintenance.
3. to control the water level sensor and remote monitoring system.



Input voltage of the solar pump motors can be AC (alternating current) or DC (direct current). If an AC pump is used, the direct current from the solar panels is converted into alternating current using an inverter. The supported power range of inverters can be adjusted according to size of irrigation systems. However, the panel and inverters must be sized accordingly to accommodate the inrush characteristic of an AC motor.

The “pump controller” in the DC powered pump system would typically include a maximum power point tracker (MPPT) to ensure that the solar array is delivering power at its peak power point. The “pump controller” in the AC powered pump system would include an MPPT as well as a DC to AC inverter in order to operate the ac electric motor which is part of the water pump. In larger systems these should be three-phase inverters to operate three-phase motors. A DC-DC Convertor is used to match the voltage output from the solar PV modules with that of the voltage required for operating the pump, preventing overvoltage.



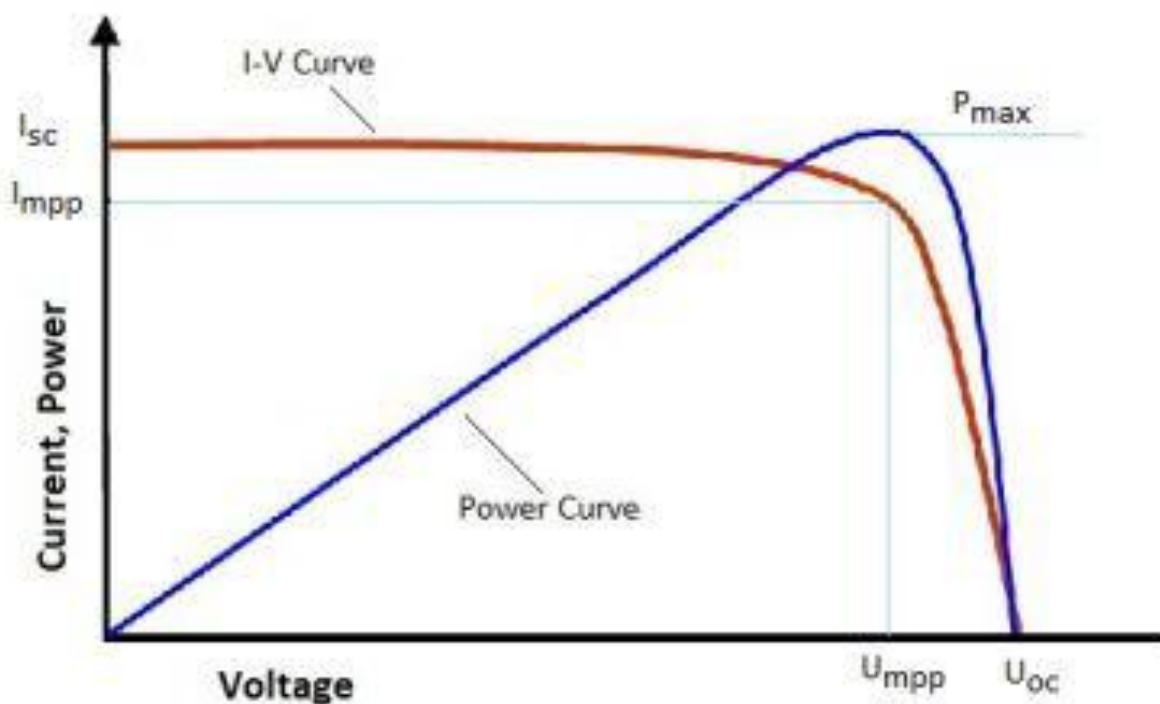
The inverter and controller must have IP54 protection or must be housed in a cabinet having IP54 protection to protect the controller from dust and water. Hybrid controllers are used sometimes too, when grid connected solar pumps are used. These controllers switch between solar power and grid power intelligently.

The following Parameters are noted in the controller by the manufacturer

- Manufacturer's name, logo or trade-mark;
- Model and Serial Number;
- Voltage Range;
- Power Range in kW for Controller; and
- Current rating (A)

11.2 Maximum Power Point Tracker (MPPT)

The output of the Solar panel is variable as it depends on the temperature and irradiance. The MPPT charge controller is a smart device that compares the panel output with the pump voltage and then determines the most optimum panel output in order to maximize the water output. The use of these solar charge controllers increases the efficiency of the whole system. The MPPT tracks the I_{mpp} and V_{mpp} every 5 seconds and forces the PV modules to operate at those voltages to get the **maximum power output**.



The pump rotational speed can be regulated according to the variation of solar irradiation: When the solar radiation intensity reaches the peak, the pump runs at its rated speed, and the output power is close to the maximum power of the PV array. When the solar radiation intensity is relatively weak, the pump runs with a lower speed based on the MPPT algorithm. When the pump speed is so low that no water flow can be available, the system stops working.

Variable Frequency Drive(VFD)

A solar pump controller matches the variable power provided by the solar array. Variable speed control ensures there is no in-rush or surge of energy during the pump/motor start-up, helping to eliminate wear on the motor and pumping system. Normally, when there is a demand for water and when solar power is available. Whenever the solar pump controller detects a need for water, the controller always “ramps up” the motor speed while gradually increasing motor voltage, resulting in a cooler motor and lower start-up current compared to conventional water systems. Due to the controller’s soft-start feature this will not harm the motor. VFD provides constant torque for a wide range of intensity of sunlight - morning till evening. So, water will be continuously pumped from morning till evening.

The VFD basically changes the frequency of the system. For a constant frequency, the voltage is also constant. So, if the frequency of the system reduces then the voltage needs to be reduced subsequently as well. The frequency is generally noted in Rotations per Minute or RPM.

In case 3 phase connection is used, VFD is needed as the starting torque is high and the initial voltage needs to be controlled. For single phase connection (for 1 or 2 HP pumps), VFD is not required, instead capacitor is used. In a single-phase connection, all the connections need to be disconnected together to prevent oversupply.

12. Advantages of using a VFD

12.1 Reduce energy consumption

A VFD with variable torque load can be used in water pumps to reduce the input energy requirement. As described by the affinity law, the power consumption of the pump can drop significantly with a small drop in the speed of the motor. Provided that the flowrate is acceptable, running a pump at a lower speed over a long period of time can deliver considerable energy saving. The VFD can reduce the operating speed of the motor, allowing a smaller PV array to be installed to deliver the pumping requirement. The ability of the VFD to control pump operation also means that in case of cloudy conditions or times of reduced solar irradiation, the motor could still run to deliver pumping work.

12.2 Reducing surge current at motor start-up

VFD can provide a reduced starting voltage to the motor windings, thus reducing the starting current of the motor and giving it time to gain momentum before the full load is supplied with power. The VFD also allows the user to start and stop the pump at a controlled, programmable rate (e.g. accelerate or decelerate over a time period) while putting minimum strain on the motor. This reduces the mechanical wear of the motor as well as the startup loads on the PV array.

12.3 Remote Monitoring System

Remote monitoring system or RMS is installed in the pump controller to record the electricity generated by the solar modules etc and sends it directly online, which is used to monitor the system performance of the solar modules and the pump. The RMS is placed in the controller box and connected to the pump controller through the wires. The data can be collected through various methods:

- A recharged SIM card inserted in the RMS

- USB drive inserted in the RMS
- SD Card installed in the RMS

13. INVERTER

Solar generators always provide DC current. Most electric motors of solar water pumps are powered by direct current (DC). Since DC motors usually have a higher efficiency than AC motors of a similar size, they tend to be preferred by solar pump manufacturers. A power inverter or inverter is a system that converts Direct Current (or DC) to an alternating current (or AC). A solarpanel produces DC current, batteries also generate DC current, but most systems we use in our daily lives use AC current. Inverters also have transformers to convert DC output voltage to any AC output voltage. Depending on the type of system (grid or off-grid) various types of inverters are available.

Water-filled brushless DC motors in particular are gaining importance because they are maintenance-free and are not affected by frequent starts/stops that are typical of solar-powered systems. Some solar pumps are still equipped with comparably cheap brushed DC motors. The main disadvantage of brushed motors is that brushes are subject to wear and tear and need to be replaced at regular intervals (approximately every two years). DC motors are mainly used for small to medium-sized irrigation schemes, while AC motors are gaining importance in applications where higher output/head combinations are required.

The controller has to have an inverter if the pump is AC. Innovations in DC/AC inverter technology have led to the development of specially designed pump inverters that can drive conventional AC motors. Non-compatible inverter/motor combinations may reduce the expected lifetime of the conventional AC motor. Therefore, well matched and tested controller/motor combinations are recommended to increase system reliability.

13.1 Types of Solar Pump Inverters

13.1.1 String Inverters

Solar panels are installed in rows, each on a string. And multiple strings are connected to one string inverter. Each string carries the DC power the solar panels produce to the string inverter where it is converted into usable AC power consumed as electricity. And based on the size of the installation, you may have several string inverters each receiving DC from a few strings.

13.1.2 Central Inverters

They are similar to string inverters but they are much larger and are able to support more strings of panels. Instead of string running directly to the inverter, as with string models, the string is connected together in a common combiner box, which runs the DC power to the central inverter where it is the converter to AC power. It requires fewer component connections, but requires a pad and combiner box. And central inverters are also best suited for large installations with consistent production across the array.

13.1.3 Micro Inverters

They have also become a popular choice for residential and commercial installations. Like power optimizers, they are module-level electronics so one is installed on each panel. And while, unlike power optimizers which don't convert, micro inverters convert DC power to

AC right at the panel and so don't require a string inverter. It also monitors the performance of each individual panel, although string inverters show the performance of each string. It makes micro inverters good for installations with shading issues or with panels on multiple panels facing various directions.

13.1.4 Battery Based Inverter

With the growth of solar and storage, battery-based inverters are becoming increasingly imperative. They are basically directional in nature, including both a battery charger and an inverter. It requires a battery to operate. They may be ground interactive, standalone grid-tied or off-grid, based on their UL rating and design. The main benefit of the inverter is that they provide for continuous operation or critical loads irrespective of the presence or condition of the grid.

The various types of battery-based inverters are:

1. *Stand-alone inverters*, used in isolated systems where the inverter draws its DC energy from batteries charged by photovoltaic arrays. Many stand-alone inverters also incorporate integral battery chargers to replenish the battery from an AC source, when available. Normally these do not interface in any way with the utility grid, and as such, are not required to have anti-islanding protection.
2. *Grid-tie inverters*, which match phase with a utility-supplied sine wave. Grid-tie inverters are designed to shut down automatically upon loss of utility supply, for safety reasons. They do not provide backup power during utility outages.
3. *Battery backup inverters* are special inverters which are designed to draw energy from a battery, manage the battery charge via an onboard charger, and export excess energy to the utility grid. These inverters are capable of supplying AC energy to selected loads during a utility outage, and are required to have anti-islanding protection.
4. *Intelligent hybrid inverters*, manage photovoltaic arrays, battery storage and utility grid, which are all coupled directly to the unit. These modern all-in-one systems are usually highly versatile and can be used for grid-tie, stand-alone or backup applications but their primary function is self-consumption with the use of storage.

13.2 Sizing of Inverter

Sizing of the inverter depends on the wattage of appliances connected to it. The input rating of the inverter should never be lower than the total wattages of the appliances. Also, it should have the same nominal input voltage as that of the battery setup. It is always better to have inverter wattage about 20-25% more than that of the appliances connected. This is specifically essential if the appliances connected have compressors or motors (like AC, refrigerator, pumps, etc), which draw high starting current. The minimum continuous watt rating of a solar water pump inverter is required to start off a submersible water pump without additional loads.

Most inverters available in the market are rated in Kilo Volt Ampere/Volt Ampere or kVA/VA. In ideal situations, (power factor of 1) 1 VA = 1 Watt. But in real power factor it varies from 0.85 to 0.99. So one can assume 1.18 VA = 1 Watt. So, if you have a setup where the total wattage of the system = 1000 Watts It means your inverter size required is more than 1180 VA or 1.18 kVA (add some extra to be on a safer side). The higher the VA of an inverter, more is the number of appliances it can support, but more costly it would be. So, it is important to size it right while buying. Also, for a grid-tied system, as there are no batteries connected, the size or VA of the inverter should match the

wattage of the PV panel for efficient and safe operation.

14. BATTERY

During optimum sunlight periods (late morning to late afternoon on bright sunny days) the pump operates at or near 100 percent efficiency with maximum water flow. However, during early morning and late afternoon, pump efficiency may drop by as much as 25% or more under these low-light conditions. During cloudy days, pump efficiency will drop off even more. Batteries can be used to store excess electrical energy produced during the peak sunlight hours and used during the non-peak hours and night to pump out water. The excess energy from the solar panels can be used to charge the battery, and used for running a small appliance like light or charging.

In a battery, two or more electrochemical cells enclosed in a container and electrically interconnected in an appropriate series/parallel arrangement to provide the required operating voltage and current levels. The battery capacity is the maximum total electrical charge, expressed in ampere-hours, which a battery can deliver to a load under a specific set of conditions. The battery available capacity is defined as the total maximum charge, expressed in ampere-hours, that can be withdrawn from a cell or battery under a specific set of operating conditions including discharge rate, temperature, initial state of charge, age, and cut-off voltage. The period during which a cell or battery is capable of operating above a specified capacity or efficiency performance level is known as battery life. Life may be measured in cycles and/or years, depending on the type of service for which the cell or battery is intended. DC produced by solar panels can be connected either directly to batteries or through solar hybrid inverters. This system includes solar modules, inverters and batteries.

14.1 Types of Batteries used in Solar Pump

14.1.1 Lead Acid

The common automobile batteries in which the electrodes are grids of metallic lead-containing lead oxides that change in composition during charging and discharging. The electrolyte is diluted sulfuric acid. The new AGM Battery technology has made a huge impact on lead-acid batteries, making it one of the best batteries to use in solar electric systems.

Industrial-type batteries can last as long as 20 years with moderate care, and even standard deep cycle batteries, such as the golf car type, should last 3-5 years. Intermediate batteries, such as the S460 and other batteries made by Surrette should last 7 to 12 years.

14.1.2 Lithium Ion Based

Lithium batteries have many advantages over traditional battery types. They have an extremely long cycle life and high discharge and recharge rates.

14.1.3 Nickel Cadmium

They are alkaline storage batteries in which the positive active material is nickel oxide and the negative contains cadmium. They are very expensive, and even more expensive to dispose of. Their efficiency is 65-80%.

14.1.4 Nickel Iron

Alkaline-type electric cells using potassium hydroxide as the electrolyte and anodes of steel wool substrate with active iron material and cathodes of nickel-plated steel wool substrate with active nickel material. They have a very long life, over 10 years, however, their efficiency is low, as much as 50%.

14.2 Sizing of PV System Batteries

If you are not going for a grid connected system or a direct connected system, you need batteries to store the energy generated using PV panels. Along with sizing of the PV panel, it is important to size the batteries as well. Because if you purchase more batteries then they will not get fully charged, if you buy fewer batteries, you may not be able to get the maximum benefit out of the solar panel.

Most big PV systems use deep cycle (or deep discharge) batteries that are designed to discharge to low energy levels and also to recharge rapidly. These are typically lead acid batteries that may or may not require maintenance. Batteries have energy storage ratings mentioned in Amp-hour (Ah) or milli-Amp-hour (mAh). They also have a nominal voltage that they generate (typically deep discharge batteries are 12V batteries). To calculate the total energy a battery can store you can use following formula:

$$\text{Units or kWh} = (\text{Volt} \times \text{Ah}) \div 1000 \text{ or } (\text{Volt} \times \text{mAh}) \div 1000000$$

Batteries should be sized in such a way that the units of energy generated by the PV system should be equal to the number we have calculated above. Now, you want the battery bank to last three days without recharging and that you use 0.6 kWh per day.

$$\text{Energy we need from the batteries} = 0.6 \times 3 = 1.8 \text{ kWh}$$

Converting this to Ah we have to divide by the voltage of your system, which can be 12, 24 or 48 V for commercial application. If we choose to use 48V, the minimum AH capacity = $1800/48 = 37.5$ Ah. Now if you divide by your battery's rating you find the number of batteries you must use.

Batteries are usually not recommended for solar-powered livestock watering systems because they reduce the overall efficiency of the system and add to the maintenance and cost. Instead of storing electricity in batteries, it is generally simpler and more economical to install 3 to 10 days' worth of water storage.

14.2.1 C10 Solar Battery

Let us just take an example of 150 Ah battery

- A 150 Ah battery at C20, will last for 20 hours on a load of 7.5 A.
- A 150 Ah battery at C10 will last for 10 hours on a load of 15 A.
- A 150 Ah battery at C5 will last for 5 hours at a load of 30 A.

C5, C10, C20 all mean the same meaning if it is rated as 150Ah. All batteries are able to supply 150 Amps for 1 hour or 1 Ampere for 150 hours. It should follow the simple rule:

$$x(\text{hours}) \times y(\text{Amperes}) = 150 \text{ if it is mentioned as } 150\text{Ah}.$$

The difference is only in the state of charge.

1. A C5 battery means it should not be discharged within 5 hours otherwise the battery life decreases
2. A C10 battery means it should not be discharged within 10 hours otherwise the battery life decreases
3. A C20 battery means it should not be discharged within 20 hours otherwise the battery life decreases

Simply, it means capacity of battery if any battery is rated 12V, 40Ah and C10, it means 10 hours of 4A charging and discharging rate. If the rating changes to C20, then 20 hours of 2A charging and discharging rate is being followed.

15 EARTHING COMPONENTS

Earthing is to ensure safety or protection of electrical equipment and humans by discharging the excess or leaking electrical energy to the earth. The purpose of earthing is to minimize risk of receiving an electric shock if touching metal parts when a fault is present. The earth rods are inter-connected to structure and lightning arrestor via earth plates. Earthing can be accomplished through bonding of a metallic system to earth. It is normally achieved by inserting ground rods or other electrodes deep inside earth. Normally charcoal and salt are added in earth pits with the rods to improve conductivity. To achieve the required driving depth – the rod couplers provide permanent electrical conductivity and the longer copper earth rods access lower resistivity soils at lower depths. The earthing rod is a 17 cm long structure of 1.5 mm diameter, made generally of copper. In case of a pipe earthing, the earthing rod is a GI rod of 30 mm diameter and 2.5 m length.

15.1 EarthingCompound

Earthing compound is a mixture of water retaining clay used to fill around the earthing pit with electrodes to help lower the soil resistivity for the easy conductivity of the electric current. Conventionally, earthing compound is a mixture of wood, coal powder, salt and sand in equal parts. Coal Powder is a good conductor of electricity, anti-corrosive and minimizes the resistivity. Salt is used as electrolyte to form conductivity between the electrode, coal and earth with humidity. Sand lets water flow easily and maintains humidity around the mixture. Coal and salt keep the soil wet as coal absorbs water keeping the soil wet.

Moisture is the controlling factor of earth resistivity. With more than 20% of moisture content, the resistivity is very little but when it is less than 20%, the resistivity increases rapidly. Water also is used to increase the conduction of electricity in soil. Now-a-days, we have pre-made mixtures like bentonite and marconite in the market. They serve the same purpose but rather more effectively.

15.2 Earthmeter

Earth meter is the instrument used to test the resistivity of the earth. If resistance of the earth is very low, the fault current through the earth electrode passes to the earth. Thus, protects the system from damage. The Earth meter helps us to keep a check on the resistivity of the earth. Resistivity of the total earthing system should be less than 1 Ohm.

Lightning Arrestor

A lightning arrester is a device used on solar power systems to protect the insulation and

conductors of the system from the damaging effects of lightning. The typical lightning arrester has a high-voltage terminal and a ground terminal. Ground terminal is connected to the earthing rod. Necessary foundation for holding the Lightning Arrestors is to be arranged keeping in view the wind speed of the site and flexibility in maintenance in future.

The lightning arrester has 4 copper spikes which attract the lightning, and therefore a separate earthing connection is required for the same.

16. WATER-LEVEL SENSOR (OPTIONAL COMPONENT)

Most commonly used water level sensor is a float switch type, which is suspended in the tank at a particular level. When water level rises it floats on the surface and gives a signal to the controller to stop the pump.

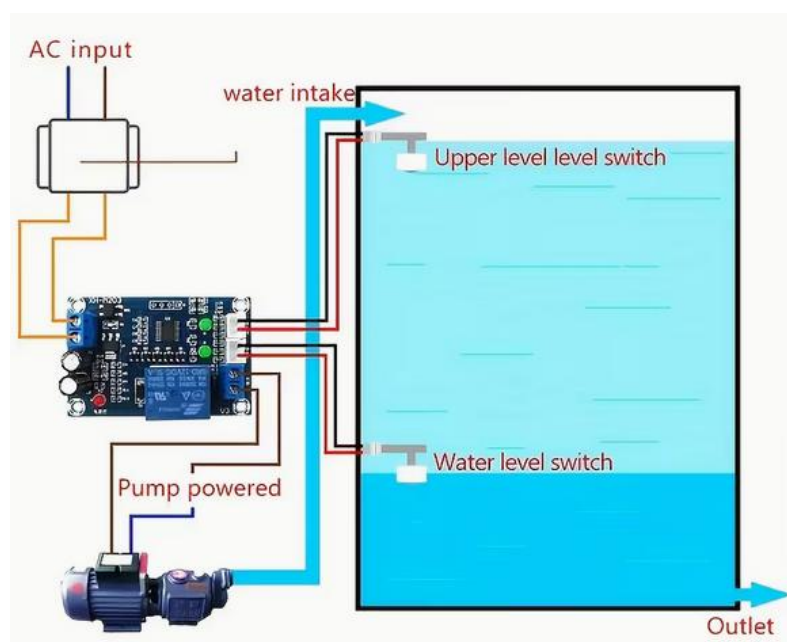


Figure 6. Pump with water storage tank

16.1 Water storage tank (Optional component)

Water pumped from the well can be stored in the storage tank. Usually this is used in drinking water applications for communities. These tanks are mostly made up of poly vinyl chloride (PVC) and are available in various shapes and sizes. Sometimes water tanks are made up of cement materials.

16.2 Open reservoirs

Open reservoirs are inexpensive and relatively easy to construct, but the big disadvantages are the high evaporation losses of water and easy accumulation of debris and sediments as well as algae growth. These effects can be significantly reduced by covering the tank, e.g. with a plastic foil. Evaporation and algae growth can be reduced when the solar panels are installed on floating mounting structures.

16.3 Elevated water tanks

This is the classic configuration of a Solar Powered Irrigation System. The pumped water is stored in an elevated water tank and irrigation functions by gravity. The elevated

tank serves as a battery where energy is stored in the form of water. The irrigation system pressure depends on the height of the water level in the storage tank. It also allows for pre-sunrise irrigation. Ready-to-use plastic tanks are available in different sizes, easy to install and do not corrode as metal or cement reservoirs do.

In order to secure a safe system operation, a water level sensor should be installed in the water tank that switches off the pump to avoid overflow. If a submersible pump is installed in a well, a second water level sensor is required to protect the pump from dry running. Such sensors are often integrated into the motor pump by default. As water tanks usually store huge amounts of water, it is important that the foundation and support structure of the water tank meets the static requirements.

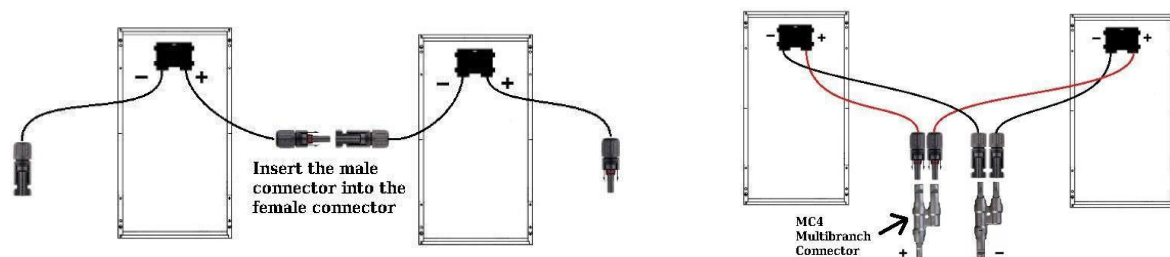
17 BALANCE OF SYSTEM

17.1 Electrical Equipments

Electrical Equipment including cables and wires that are used for networking in the system. It also includes MC4 connectors, circuit breakers and inverters used in current and voltage management.

17.2 MC4 Connectors

MC4 Connectors are single contact electrical connectors used for connecting solar panels. MC stands for manufacturer multi-contact and 4 for the 4 mm diameter contact pin. They are used because they make wiring solar arrays much simpler and faster. The connectors come in both male and female types which are designed to be put together. They have a special locking mechanism and need a MC4 unlocking tool to separate the connectors. For connecting solar modules in series, a female MC4 connector with positive lead of one solar module is connected to a male MC4 connector with negative lead of adjacent solar module.



For connecting solar modules in parallel, we need additional equipment called MC4 multi branch connectors. There are two different types of multi branch connectors for both positive and negative leads. When connecting, two male MC4 connectors are connected to a MC4 multi branch connector that suits and has male MC4 connector for its output and two female MC4 connectors are connected to MC4 multi branch connector that takes female MC4 connectors as input and has a female MC4 connector for its output.

17.3 Miniature Circuit Breakers

Automatic Circuit Breakers are used in the pump controller to protect from overload or short circuit. The regulated current of the circuit breakers are chosen based on the power and size of the pump.

17.4 Distribution Board

A distribution board (also known as panel board, breaker panel, or electric panel) is a component of an electricity supply system that divides an electrical power feed into subsidiary circuits. ACDB / DCDB are an important part of the Solar PV system to provide extra electrical protection to the system during failures.

Table 5..2% Voltage drop chart

	In sq mm									
	2.5	4	6	10	16	25	35	55	70	
	AWG									
Nominal Ampacity (Amps)	#14	#12	#10	#8	#6	#4	#2	#1/0	#2/0	#4/0
1	45	70	115	180	290	456	720	-	-	-
2	22.5	35	57.5	90	145	228	360	580	720	1060
4	10	17.5	27.5	45	72.5	114	180	290	360	580
6	7.5	12	17.5	30	47.5	75	120	193	243	380
8	5.5	8.5	11.5	22.5	35.5	57	90	145	180	290
10	4.5	7	11.5	18	28.5	45.5	72.5	115	145	230
15	3	4.5	7	12	19	30	48	76.5	96	150
20	2	3.5	5.5	9	14.5	22.5	36	57.5	72.5	116
25	1.8	2.8	4.5	7	11.5	18	29	46	58	92
30	1.5	2.4	3.5	6	9.5	15	24	38.5	48.5	77
40	-	-	2.8	4.5	7	11.5	18	29	36	56
50	-	-	2.3	3.6	5.5	9	14.5	23	29	46
100	-	-	-	-	2.9	4.6	7.2	11.5	14.5	23
150	-	-	-	-	-	-	4.8	7.7	9.7	15
200	-	-	-	-	-	-	3.6	5.8	7.3	11

Source: <http://www.affordable-solar.com/learning-center-tools/wire-sizing>

17.4.1 Solar DCDB (Direct Current Distribution Box), is used to protect the system if there is any fault during failure on the DC side. Here the electricity supply system divides an electrical power feed into subsidiary circuits. It contains a protective fuse or circuit breaker to switch the system off during fault. DCDB controls the DC power from Solar Panels and has a necessary surge protection device (SPD) and fuses to protect the solar panels strings and solar inverter from any type of damage.

17.4.2 Solar ACDB (Alternative Current Distribution Box), receives the AC power from the solar inverter and directs it to AC loads through the distribution board. ACDB includes necessary surge protection devices (SPD), Voltage, Current monitoring and MCCB to protect the solar inverter from any type of damage or heavy voltage.

17.4.3 Array junction box (AJB), is referred to as solar PV junction box or combiner box. It collects DC power from PV strings and then transfers either directly or through a main junction box (MJB) to the power inverter. The power inverter converts the DC power to AC which after metering is used to measure the power consumption in ON-Grid/OFF-Grid/Hybrid system.

17.5 Wires and Wiring Size

Solar water pumping systems are typically provided with all wiring appropriate for the installation. This is why it is important to determine the distances between the solar array and water pump during the site visits. This is particularly important for borehole/well

pumps because of the water-resistant cable that must be used to connect the pump.

A properly designed wiring system should have a voltage drop of not more than 5%, and, therefore, on a 12V system, voltage loss should not be more than 0.6V. The wire-sizing chart below should be used to select the correct wire cross section for a given current and length of wire. The voltage loss values given in the table are for 100m length of wire at a given current. The table can be used for lengths of wire that are less than 100m by first dividing the selected length by 100 and multiplying by the corresponding voltage drop given.

It must be noted that voltage losses in the table are theoretical, calculated using Ohm's Law. As such the state of wires must be considered. Generally insulated copper wires of 2 mm diameter are used for connections in the solar arrays, pumps and controllers. Also, for long distance transmission in case the pump is located far from the location of the solar array, aluminium wires are used.

The pump controller is connected to the pump and solar array using a 3-phase connection and lug. The lug is opened; wires are inserted in the live neutral and earth wire positions on either side. The colour coding is followed, and crimped and connected. The colour coding followed in 3-phase conductor is red, yellow and blue wiring, along with black wire for neutral and green wire for earthing. Once repacked, the connection is sealed with waterproof covering using a compound rubber strip. Splice kit is used to waterproof the connection, for otherwise short circuits can happen during heavy rains.

17.6 Mechanical Equipments

Mechanical equipment consists of pipes and other plumbing gears. The selection of pipes is done by checking their pressure and temperature rating, ease of fabrication and Suitability for outdoor application. PVC pipes are generally used, and the diameter of the pipes vary according to the size and head (in case of submersible pump).

17.7 Safety Equipments

Safety equipment including earthing materials and personal protection gears. For full protection against open circuit, accidental short circuit and reverse polarity, the components need to be Earthed using an earthing rod. For personal protection, rubber gloves, boots and insulated tools are to be used when working on the system.

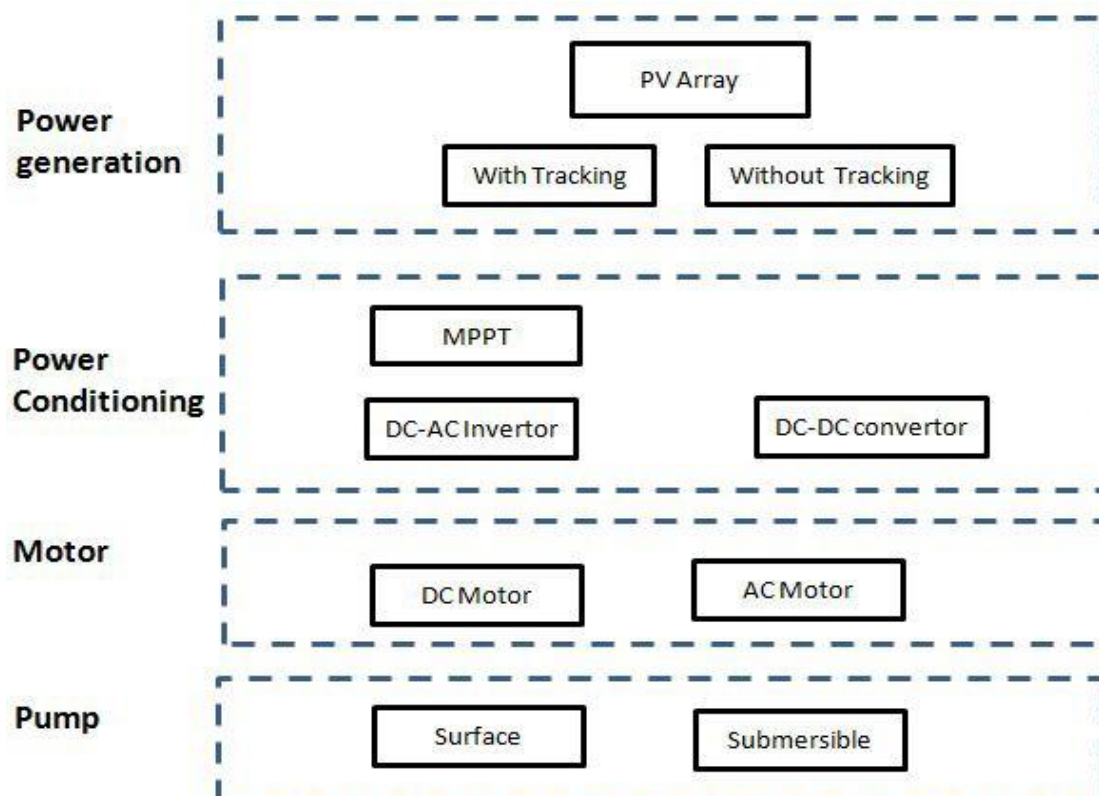
				
Safety Helmet	Safety goggles, preferably with side shields	Protective safety shoes	Protective Gloves	Hearing Protection

A first aid kit needs to be carried by the installation team in case of any mishaps. The Solar water pumping system should be provided with overvoltage protection. The aim is to reduce the over-voltage to a tolerable value before it reaches the PV or other subsystem

components. The source of over voltage can be lightning or another atmospheric disturbance.

17.8 IP Rating of Exposed Components

The Ingress Protection or IP is a rating system designed to check the protection of the components of the pumping system from solid and liquid damage. The first digit in the rating represents the protection level against solids and the second digit indicates protection level against liquid damage. The submersible pumps are usually rated IP56 or above (the liquid protection rating needs to be 6 or higher for submersible pumps, since the pump is submerged in water constantly).



Paired with the right environmental conditions, the right amount of PV panels and controllers and the right installation setup of energy storages, converters, inverters, pumps and motors — the solar water pumping system can present a farm and a nation with numerous benefits.

18. CONCLUSION

The analysis and evaluation of photovoltaic (PV) solar water pumping systems confirm their viability and superiority as a sustainable approach to improve water utilization efficiency. Key Conclusions to this article include:

Environmental Sustainability: PV systems are highly environmentally friendly, producing nearly zero greenhouse gas emissions or pollutants during operation, unlike fossil fuel-based pumps. This aligns with global Sustainable Development Goals (SDGs) related to clean water, clean energy, and climate action.

Economic Viability: While initial capital costs can be high, the life-cycle cost (LCC)

of PV systems is significantly lower than diesel alternatives due to minimal operating expenses (zero fuel cost) and low maintenance requirements. Payback periods are often short, making them a cost-effective long-term investment.

Technical Reliability and Efficiency: PV water pumping systems are technically reliable, especially in off-grid or remote areas with abundant sunlight. Their performance is directly correlated with solar radiation, naturally matching periods of peak water demand for applications like irrigation. Advances in technology, such as Maximum Power Point Tracking (MPPT) techniques and optimized system designs (e.g., using water storage instead of batteries), further enhance their overall efficiency and stability.

Improved Water Utilization: By providing a consistent and reliable water supply, these systems support efficient irrigation practices (like drip irrigation), which minimize water losses and enhance crop yields, thereby improving overall water utilization efficiency.

Socio-Economic Impact: The adoption of these systems can lead to positive socio-economic impacts in rural communities by reducing labor burdens, enhancing food security and economic independence for farmers, and promoting resilient rural development.

Photovoltaic solar water pumping is a robust, efficient, and sustainable solution for water management, particularly in regions with limited infrastructure. Successful implementation depends on proper system design and sizing tailored to local conditions and water demands, with ongoing monitoring and supportive policies to maximize their impact.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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HIGH-IMPACT OPTIONS FOR A RENEWABLE ENERGY CLEAN ENVIRONMENT AND HEALTHY NIGERIAN ECONOMY

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ABSTRACT

High-impact renewable energy is the most rapidly expanding energy source globally. Despite its subordinate status in Nigeria relative to conventional energy sectors, our principal trading partners and numerous prominent multinationals are allocating hundreds of millions of dollars towards high-impact renewable energy in anticipation of forthcoming transformations in global energy markets. As Nigeria deliberates on strategies to combat climate change, the nation's high-impact renewable energy sectors aim to guarantee that Nigerians have access to all available options. Consequently, they have united to develop alternatives for a pristine environment and a robust Nigerian economy. This study acknowledges the absence of a singular answer to climate change and delineates a crucial array of actions that, in conjunction with additional strategies, would enable Nigeria to attain its long-term economic and environmental objectives.

This study emphasises the opportunities linked to Nigeria's substantial renewable energy resources. These are renewable resources that are renewed by the Earth's natural cycles and exert little effects on the environment and human health. They encompass wind, solar, geothermal energy, run-of-river hydroelectricity, and sustainable biomass fuels. These resources can substitute fossil fuels in various domains, including power generation and space and water heating. Fuel cells, while not a renewable resource alone, represent a promising technology that, when integrated with renewable sources, can provide diverse and impactful electricity. The paper also delineates prospects linked to the augmented utilisation of passive renewable energy and energy efficiency in structures.

This paper further delineates three principal strategies for Nigeria to establish a high-impact

renewable energy sector and their prospective contributions to mitigating the nation's greenhouse gas emissions. They are specifically a) fostering the establishment of a high-impact renewable electricity market (4.1 Mt), b) promoting the utilisation of consumer-oriented renewable energy technologies, and c) advocating for enhanced passive renewable energy and efficiency measures. A set of complimentary measurements was established for each of these possibilities. The initiatives outlined in this paper if well and promptly executed will diminish future costs associated with addressing climate change by enhancing Nigeria's capacity to mitigate and prevent emissions proactively.

1. INTRODUCTION

Solar energy can be directly harnessed through several devices. Solar thermal technologies transform solar energy into thermal energy for the purpose of heating water and air. Applications encompass solar water heating systems and solar walls for extensive space heating. The expenses associated with most solar thermal solutions are readily recouped by fuel savings over their operational lifespan. Photovoltaics (PV) transform solar energy into electrical power. Photovoltaic technology yields operational cost reductions in numerous on-grid and off-grid applications. In recent years, the global yearly growth rate for photovoltaic sales has exceeded 25%. Passive solar employs architectural strategies to harness and retain solar energy for temperature control in residential and commercial structures.

Wind energy is the most rapidly expanding energy source globally and has experienced cost reductions exceeding 50% in the past decade. Wind turbines harness wind energy and convert it into electricity. They are available in various sizes, and numerous European manufacturers are currently producing individual wind turbines sufficiently large to supply electricity for over 500 houses.

Earth energy refers to solar energy that is absorbed by the Earth and stored a few meters beneath the surface. This free energy can be harnessed and enhanced to beneficial temperatures with a ground-source heat pump. This heat can subsequently be supplied as hot air or water for home or commercial space heating. The procedure can likewise be inverted for air-conditioning. In numerous instances, the expenses associated with geothermal energy systems are readily recouped through fuel savings over the technology's lifespan.

Run-of-river hydroelectricity employs a turbine to produce electricity from naturally flowing water, without the construction of a dam for water storage expressly intended for power generation. Run-of-river hydro power is economically viable in the long term and can generate substantial electricity when situated near the electricity demand. Micro and mini-hydro technologies, utilising free-flowing water, are frequently cost-effective for small-scale generating in rural or distant areas.

Biomass fuels are derived from diverse agricultural crops, wood, and agricultural byproducts. Ethanol exemplifies a biomass fuel that is frequently utilised as a petrol additive. Most vehicles may utilise gasoline with a significantly higher ethanol concentration without compromising performance, whilst diminishing hazardous emissions.

This study emphasises the prospects linked to Nigeria's substantial renewable energy resources. These are renewable resources that are renewed by the earth's natural cycles and exert little effects on the environment and human health. They encompass wind, solar, geothermal energy, run-of-river hydroelectricity, and sustainable biomass fuels. These resources can substitute fossil fuels in various domains, including power generation and space and water heating. Fuel

cells, while not a renewable resource alone, represent a promising technology that, when integrated with renewable sources, can provide diverse and impactful electricity. The document also delineates prospects linked to the augmented utilisation of passive renewable energy and energy efficiency in structures.

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2. LITERATURE REVIEW

In recent years, the 'energy question' has increasingly taken precedence over other choices, strategies, and policies related to human survival and progress. Contemporary societies heavily rely on dependable, cost-effective, and sustainable energy sources. Energy is a needed input for the majority of production processes and economic activities, as well as a fundamental aspect of daily life. Enhanced access to contemporary energy services is essential for social and economic advancement (Oyedepo, 2014a).

Currently, the bulk of global energy supplies are sourced from fossil fuels (including natural gas, oil, and coal), resulting in the ongoing depletion of these resources and causing detrimental environmental effects. Numerous individuals are apprehensive about these issues and seek to urgently mitigate the symptoms; nonetheless, not all comprehend the fundamental causes and, therefore, fail to recognise that both technology and social transformations are necessary. It is now universally recognised that renewable energy capacity must be augmented by harnessing its vast potential (Lorenzini et al., 2010). Therefore, the advancement and implementation of clean, renewable energy is essential for the economic and environmental welfare of any nation. Renewable energy is crucial for fulfilling future energy requirements and attaining sustainability. Nonetheless, its proliferation and implementation have been sluggish over the past decade due to diminished fossil fuel prices and obstacles within the energy industry. Stringent methodologies are essential to expedite the advancement and application of renewable energy, hence enhancing its role in the existing energy supply compositions (Nnaji et al., 2010).

The necessity for emerging nations to improve their renewable energy initiatives will create economic prospects for trade-oriented cities. The utilisation of renewable energy in developing nations such as Nigeria is now somewhat restricted, despite the belief in its considerable potential (Oyedepo, 2012a).

Owing to numerous financial and technical limitations, renewable energy remains underutilised in Nigeria. Nigeria remains significantly reliant on fossil fuels. The adverse effects on the environment and the economic strain resulting from the inefficient utilisation of fossil fuels must be mitigated by the implementation of suitable technology, national energy policies, and management strategies. Nevertheless, social and economic growth, together with poverty alleviation, are the paramount concerns of Nigeria. Renewable energy (RE) sources could fulfil the energy demands necessary for the urgent socioeconomic development of this country. Therefore, to advance renewable energy technologies (RETs) in Nigeria, more efficient and adaptive policies are necessary to address the immediate demands of the populace.

An energy-poor country is characterised by its residents' inability to access electricity sufficient to fulfil fundamental need, like lighting and cooking. A significant portion of the population in developing nations, such as Nigeria, is adversely impacted by their minimal energy usage, while others rely on polluting fuels or invest excessive time procuring fuel to satisfy their fundamental necessities (Emodi and Boo, 2015). The Energy Poverty Action Initiative of the World Economic Forum (IEA, 2007) states, "Access to energy is essential for enhancing quality of life and is a critical requirement for economic development." Inadequate access to electricity in Nigeria evidently results in heightened poverty, subpar economic performance, restricted employment opportunities, and challenging possibilities for institutional development. The rapid population expansion signifies that the nation's energy need will persistently escalate, akin to the substantial rise in energy demand prompted by the worldwide population surge and industrial revolution of the 20th century (Mohammeda, 2013). The energy crisis in Nigeria has significantly impacted public electricity consumers. This scenario has unequivocally forced most households in both rural and urban areas of the country to heavily rely on combustible renewable energy sources, particularly for domestic heating and cooking. Fuelwood and charcoal are prevalent energy sources frequently utilised in Nigeria. Universally accessible energy services, characterised by renewable resources that are sufficient, economical, dependable, high-quality, safe, and environmentally friendly, are essential for sustainable development and poverty alleviation in the nation.

The primary aims of this study are to: (i) evaluate energy resources in Nigeria and the current state of the power sector; (ii) examine the potential and utilisation of renewable energy sources (solar, wind, small hydro, and biomass) in Nigeria; (iii) analyse the factors hindering the development of renewable energy technologies in Nigeria; and (iv) assess the roles of decentralised renewable energy systems in achieving sustainable energy in Nigeria. Electricity, being a vital resource for contemporary society, is crucial for future societal growth. This commodity must be delivered consistently to meet everyday demands. The performance and efficiency of the power generation industry are crucial for ensuring a quality and reliable electricity supply. Uninterrupted access to high-quality energy infrastructure is crucial for enduring economic growth and development. The insufficient supply of power might hinder the development of industries, small enterprises, hospitals, and the installation of other infrastructure facilities in both urban and rural areas (Oyedepo et al., 2012).

The power sector is a fundamental component of global economic development; its advancement relies on aligning quality with energy services, since this is the sole method to provide a foundation for stable and robust economic growth. The Ministry of Economy (2002) asserts that the power sector is a vital component of a country's economic activity, serving as a dynamic factor and possessing unquestionable strategic significance for other sectors of the economy. Consequently, the provision of power under ideal conditions of security, quality, and cost must remain an unwavering priority in the formulation of a nation's energy policy.

One method to address the increasing energy demand in a developing nation such as Nigeria is to establish an appropriate and sustainable power generation system. Nigeria's electricity sector is facing significant issues due to outdated equipment, insufficient generation and transmission capacities, and elevated aggregate technical and commercial losses. These difficulties arise from years of neglect, mismanagement, and insufficient finance. The issues intensified due to a substantial surge in electricity demand stemming from economic and demographic expansion.

The electrical grid is inconsistent and inadequate to satisfy increasing demand, leading to recurrent load-shedding and other disruptions. This has also restricted the bulk of Nigerians' access to clean and modern energy services. Furthermore, the erratic nature of the country's electrical supply has led to extensive self-generation of power from alternative sources in Nigeria; the affluent predominantly depend on generators, resulting in a 75% rise in the consumption of petroleum products in 2012 (Udoudoh and Umoren, 2015).

Approximately 62% of Nigerians depend on wood fuel for their energy requirements due to insufficient power, leading to significant deforestation in the nation (Babanyara and Saleh, 2010; Eleri et al, 2012; Zubairu et al., 2015). The reliance on firewood presents a significant indoor pollution risk and resulted in about 79,000 fatalities in Nigeria due to smoke inhalation in 2011 (Eleri and Onuvae, 2011). A 2013 research by the World Health Organisation indicated that smoke inhalation from firewood used by women resulted in 98,000 fatalities (Emodi and Boo, 2015).

In the past decade, the Nigerian power sector has pursued optimal strategies to enhance power availability in the nation. In 2005, the federal government initiated a series of extensive programs for electricity reform. The National Electric Power Authority (NEPA), the exclusive electricity provider, was succeeded by the Power Holding Company of Nigeria (PHCN), which was divided into six generation companies (GenCos), eleven distribution companies (DisCos), and the Transmission Company of Nigeria (TCN) (Wijeratne and Omontuemhen, 2016). The National Assembly enacted the Electric Power Sector Reform Act in 2005, leading to the inauguration of the Nigerian Electricity Regulatory Commission (NERC) on November 1, 2005, tasked exclusively with regulating power sector activities, including tariff structures (Okafor, 2017). The Rural Electrification Agency (REA), an autonomous entity, was established to monitor advancements and ensure transparency in the power sector. Initiatives were implemented to diversify the power sector through agreements for investments in hydropower, nuclear energy, and various renewable energy sources. In 2010, a Roadmap for Power Sector Reform was established, privatising the generating and distribution businesses, although the transmission of power remained under state ownership. The Nigeria Bulk Electricity Trading Plc (NBET) was established to engage in the procurement and resale of electric power and ancillary services from independent power producers and successor generation firms (Idemudia and Nordstrom, 2016).

The primary aim of the power sector reform is to establish an electricity supply business in Nigeria that adequately fulfils the requirements of its population in the twenty-first century. Others want to modernise and enhance electricity access while fostering national, economic, and social growth (ECN, 2014). Regrettably, despite the commitment of both public and private sectors to enhance the power ecosystem through investment, heightened competitiveness, and deregulation since the initiation of the reform process in 2010, there has been no substantial advancement in the power sector. The fundamental issue of inadequate power persists unresolved, with minimal prospects for improvement, while prices continue to escalate. Nigeria's electricity infrastructure capabilities still have a considerable distance to cover to match those of other growing economies. The primary emphasis must be on eliminating or at least mitigating the principal obstacles to the generation, transmission, and distribution of power across the nation.

3. THREE PRINCIPAL OPTIONS RECOGNISED BY NIGERIA'S HIGH-IMPACT RENEWABLE ENERGY SECTOR

Three principal choices identified by Nigeria's high-impact renewable energy sector and their potential contributions to mitigating the nation's greenhouse gas emissions are as follows. A series of complimentary measures has been formulated for each of these alternatives.

3.1 Fostering the Advancement of a High-Impact Renewable Electricity Market (4.1 Mt)

- a) Consumer information regarding power items (enabling measure);
- b) Market-wide incentives for high-impact generation (consumer credit, production credit, Renewable Portfolio Standards);
- c) Acquisition of green power (0.4 Mt);
- d) Elimination of tax impediments to renewable energy generation (1.4 Mt);

3.2 Facilitate the Adoption of Consumer-Oriented Renewable Technologies

- a) Net metering (0.1 Mt);
- b) Consumer credit for rural renewable electricity generation (0.5 Mt);
- c) Partnership between municipalities and the federal government for 50,000 solar rooftops (0.4 Mt);
- d) Expedited funding for on-site renewable energy and water heating (2.0 Mt);
- e) Minimum biomass fuel content in petrol (3.1 million tonnes).

3.3 Promote Enhanced Utilisation of Passive Renewable Energy and Energy Efficiency (3.2 Mt)

- a) Low-cost loan for R-2000 residences (0.5 Mt);
- b) Low-interest loans or tax incentives for household energy-efficient retrofits (1.4 Mt).

Significant insights can be gleaned from industries that include renewable energy sources into their operational frameworks. The subsequent are essential lessons that others may derive:

- a) The current technology can substantially aid Nigeria in fulfilling its carbon reduction obligations. Although focused R&D expenditure is essential for certain technologies, the immediate emphasis should be on cultivating and advancing the markets for clean technologies that are currently exhibiting significant market share gains in other nations.
- b) The strategies for addressing climate change may yield a net economic advantage for Nigeria. Numerous measures delineated in this document are classified as "no-regrets" solutions, indicating that ancillary advantages such as job creation and diminished healthcare expenditures warrant their execution irrespective of their capacity to mitigate GHG emissions.
- c) The sooner Nigeria adopts strategies to address climate change, the more advantageous the outcomes for its citizens.

4. THE IMMINENT ENERGY REVOLUTION

The world is poised for an energy revolution. Shell International's evaluation of worldwide trends suggests that substantial market transformations will transpire in the energy sector during the forthcoming decades. Both Shell and BP-Amoco have declared their intention to invest hundreds of millions of dollars to position themselves for a market where they anticipate renewable energy would account for 5%-10% of the global energy supply by 2020 and 50% by 2050.

In an article entitled "The Future of Energy," The Economist posits that the swift reduction in renewable energy costs may compel the formidable \$1 trillion per annum fossil fuel industry to recede early in the next century. ² The report states that wind energy is nearing price parity

with fossil fuels, with costs approximately 50% of their 1990 levels. In contrast, the paper predicts a dismal future for nuclear and large hydro energy, despite the fact that governments in most industrialised nations continue to allocate a disproportionately larger share of their energy research and development funds to nuclear compared to renewables.

Although several stakeholders in Nigeria's fossil-fuel sector caution that the necessary actions to combat climate change may result in economic catastrophe, numerous others contend that these steps will generate opportunities. Michael Porter and Claas van der Linde assert in their essay "Green and Competitive" in the Harvard Business Review that pollution results from inefficiency, and well-crafted environmental legislation can stimulate innovation and reduce costs. Three The authors assert that "managers must begin to perceive environmental enhancement as an economic opportunity" and that "resisting innovation will result in a decline in competitiveness in the contemporary global economy."

These arguments pertain not alone to corporations, but also to nations. Countries such as the U.S., Britain, Japan, and Germany are either in the midst of enacting or have already enacted robust regulatory measures to promote the growth of domestic renewable energy markets. Nigeria, however, has made what could be charitably termed as "incremental progress" in its preparations for the impending energy revolution.

Nigerians face a decision to make. We can capitalise on the impending energy revolution and establish early-mover advantages in both our economy and environment. Alternatively, we may persist in permitting our economic liabilities and social costs to escalate, subsequently importing climate change solutions at a significantly elevated cost in the future.

5. THE HEALTH BENEFITS OF RENEWABLE ENERGY

The fossil fuel emissions that most significantly affect human health include nitrogen oxides (NO_x), sulphur dioxide (SO₂), and particulate matter (PM). Recent studies reveal that roughly 1 in 13 non-traumatic fatalities in Nigerian cities is attributable to air pollution resulting from fossil fuel combustion. Four This incurs substantial expenses for Nigerians and the Nigerian healthcare system.

Renewable energy sources can deliver cleaner electricity, mitigating climate change and offering more affordable energy to all. However, are you aware that renewable energy also offers considerable health advantages? The World Health Organisation (WHO) reports that around 99% of the global population inhales air daily that fails to comply with WHO air quality criteria, hence jeopardising their health. Renewable energy sources such as wind and solar can enhance air quality and mitigate health hazards for the global population. Mitigating greenhouse gas emissions benefits not just the environment but also human health. Renewable energy benefits contribute to enhanced health through improved air quality and diminished sickness risk. What are the advantages of renewable energy? We examine the potential of renewable energy sources to enhance public health by mitigating pollution. Recent studies indicate that approximately 1 out of every 13 non-traumatic deaths occurring in Nigerian cities can be attributed to air pollution from the burning of fossil fuels.⁴

5.1 Diminished Risk of Respiratory Ailments

The combustion of fossil fuels significantly contributes to health-related concerns due to the emission of detrimental gases such as nitrogen oxide, sulphur dioxide, and carbon dioxide. These gases can induce respiratory ailments such as asthma and may aggravate these conditions, resulting in hospitalisation. Utilising renewable energy sources in lieu of fossil fuels

diminishes the emission of these gases into the atmosphere, potentially mitigating respiratory ailments and reducing the risk of exacerbating the conditions of individuals already afflicted. Enhancing indoor air quality is achievable by retrofitting your residence to increase efficiency and establish a cleaner domestic atmosphere.

5.2 Reduced Incidence of Myocardial Infarctions and Cardiovascular Disorders

Besides respiratory ailments, the combustion of fossil fuels, such as coal, exacerbates other health concerns, including heightened risk of myocardial infarction and cardiovascular disorders. A significant advantage of renewable resources is enhanced air quality and a reduction in environmental contaminants, which may mitigate the incidence of cardiovascular diseases in the populace.

5.3 Reduced Health Care Expenditures

The health problems linked to fossil fuels significantly burden the Nigerian economy. In 2011, Dr. Paul Epstein, Associate Director of the Centre for Health and the Global Environment at Harvard Medical School, published a report in the Annals of the New York Academy of Sciences estimating the health impacts of fossil fuels to be between \$345.3 billion and \$543.3 billion. Shifting from fossil fuel combustion to renewable energy sources might yield substantial financial savings for the nation and enhance public health outcomes. In addition to significant economic advantages, renewable energy offers personal financial enhancements through incentives such as solar tax credits and rebates.

5.4 Enhanced Air Purity and Improved Air Quality

Improved air quality in our surroundings correlates with enhanced health. Subpar air quality leads to respiratory disorders, cardiovascular diseases, neurological complications, cancer, and diminished life expectancy. A primary advantage of clean energy is the enhancement of air quality, which diminishes the likelihood of health issues.

5.5 Reduced Contamination in Water Supply

Fossil fuels not only contaminate the atmosphere but also use and degrade substantial quantities of the water supply, hence restricting resources available for potable water and essential sectors such as agriculture. One advantage of wind energy and other renewable sources, such as solar, is their minimal water requirement for operation, which may alleviate water scarcity concerns and enhance water quality.

5.6 Enhanced Quality of Life

Although decreasing fossil fuel consumption would not eradicate current health conditions, it can enhance the quality of life for individuals afflicted with asthma and other respiratory ailments. The advantages of renewable resources also encompass enhanced quality of life and increased longevity by diminishing the prevalence of several diseases through the establishment of a cleaner environment and atmosphere.

5.7 Diminished Risk and Incidence of Cancer

Reduced contaminants in the air and water result in diminished exposure to deleterious gases and fine particles that may cause severe and potentially fatal diseases like as cancer. Individuals residing in regions with lower pollution levels experience a diminished risk of developing these diseases, which constitutes one of the primary health advantages of renewable energy.

5.8 Extended, Healthier Lifespans

Besides enhancing mental and emotional well-being, renewable energy sources can contribute

to longer, healthier lives. These sources may mitigate the risk of physical health problems associated with air and water pollution, alleviate fuel scarcity, and lessen financial burdens on more disadvantaged communities.

5.9 Enhance Mental and Emotional Well-Being

Nonrenewable energy sources are finite and might result in "fuel scarcity." Limited resources induce financial strain and stress, potentially resulting in mental, emotional, and physical health difficulties. Moreover, inadequate air quality linked to nonrenewable energy sources, particularly coal, may adversely affect both physical and mental health. Renewable energy sources may mitigate some of these problems. One significant health benefit of solar energy and other renewable sources is enhanced mental and emotional stability for all, alongside the establishment of a cleaner, healthier environment. Investigate solar energy and its comparison to fossil fuels.

5.10 Mitigate Neurological Injury

The combustion of fossil fuels such as coal results in air and water pollution, which is associated with numerous severe health problems, including neurological impairment. Clean energy methods, such as solar and wind power, do not generate the air and water pollution associated with nonrenewable energy sources, hence mitigating the risk of neurological disorders and enhancing public health. Investigate supplementary advantages of renewable energy beyond their impact on human health.

5.11 Mitigated Premature Mortality

The numerous health complications linked to fossil fuel combustion, such as cardiovascular and respiratory ailments, can lead to an increase in premature mortality, hindering individuals from achieving longer, better lives. Renewable energy sources can enhance air and water quality, hence extending life expectancy for numerous individuals, particularly within our most at-risk populations.

6. THE ECONOMIC BENEFITS OF RENEWABLE ENERGY

Renewable energy has environmental, social, and economic advantages. A recent analysis by the International Renewable Energy Agency (IRENA) indicates that doubling the present contribution of renewable energy in the global energy mix could elevate world gross domestic product (GDP) by up to 1.1 percent, or over \$1.3 trillion, by 2030. It is crucial for industry and corporate management to acknowledge that environmental enhancement represents an economic opportunity, and that rejecting innovation would result in a decline in competitiveness within the contemporary global economy.

A 1997 study by the Pembina Institute for Environment Nigeria revealed that investments in energy efficiency and renewable energy generate significantly greater employment compared to equal investments in traditional energy supply. ⁹ The analysis indicated that each million dollars invested generates an average of 36.3 employment in the energy efficiency industry and 12.2 jobs in the renewable energy sector. Each million dollars allocated to conventional energy generates an average of merely 7.3 jobs. The initiatives outlined in this article would yield a net increase exceeding 100,000 person-years of employment.

The Pembina analysis indicates that elevated employment levels are mostly due to the labour-intensive nature of the work and the jobs generated from the reinvestment of energy savings. A further benefit pertains to the nature of employment opportunities generated. Investments in renewable energy and energy efficiency generate jobs with extensive regional distribution, are

continuous, and require minimal employee relocation.

The analysis indicated that moderate government investment in energy efficiency and renewable energy can catalyse substantial private investment. Each million dollars of government expenditure typically generates six million dollars in private-sector investment. Renewable energy offers numerous direct and indirect economic advantages at both micro and macro levels. Presented below are few examples:

6.1 Employment Generation

Over 10 million individuals are employed in the global renewable energy business, with an addition of over 500,000 new positions in 2017. The sector offers a variety of employment opportunities, encompassing roles in production, installation, engineering, sales, marketing, and further fields. Employment opportunities in renewable energy are projected to expand significantly in the foreseeable future. The U.S. Bureau of Labour Statistics (BLS) projects a 105 percent increase in the solar photovoltaic installer profession and a 96 percent rise in demand for wind turbine service specialists from 2016 to 2026. This designates the #1 and second fastest-growing occupations in the United States.

6.2 Income of Landowners

Renewable energy additionally offers an alternative revenue stream for rural landowners and agricultural producers. Data from the American Wind Energy Association (AWEA) indicates that wind farms in the U.S. contribute approximately \$222 million annually to rural landowners hosting these installations on their property. Agriculturalists can generate revenue by cultivating crops designated for biofuel production. Corn ethanol is presently the primary means by which farmers engage in the energy sector, although alternative biofuels are beginning to receive increased attention.

6.3 Decreased Energy Expenditures

Transitioning to renewable energy is an effective method for residential, commercial, and industrial energy consumers to reduce their expenses. Installing solar panels on your property enables you to produce your own electricity, perhaps reducing your energy expenses to zero. The precise amount you save is contingent upon various circumstances, including your location. EnergySage reports that typical savings vary from \$10,483 in Washington to \$30,523 in Massachusetts.

6.4 Enhanced Real Estate Valuation

Installing renewable energy systems on your house can substantially enhance its value. Installing solar panels on your residence increases its worth by roughly \$20 for each dollar saved on energy expenses. Homeowners may recover a substantial portion of the expense incurred from installing solar modules upon selling their property. Incorporating solar panels into your residence may facilitate a swifter sale.

6.5 Energy Autonomy

Increased utilisation of renewable energy could enable the United States to attain energy independence—fulfilling domestic energy requirements and diminishing reliance on foreign nations, as well as vulnerability to fluctuating international energy prices. Augmenting the proportion of renewable energy in the U.S. energy portfolio could further diminish dependence on foreign oil. Furthermore, renewable energy sources are inexhaustible, allowing the nation to rely on this autonomy in the long term.

6.6 Consistent Energy Pricing

Establishing renewable energy installations necessitates a significant initial investment; however, subsequent operational costs are minimal. This is primarily due to the absence of a gasoline purchase requirement. Reducing fuel expenses decreases the production cost of power. This indicates that the price of electricity is not influenced by fluctuations in fuel prices, such as those of natural gas or coal. This could result in more stable energy prices in the long term.

6.7 Mitigation of Climate Impacts

A new analysis from the Universal Ecological Fund indicates that climate change has incurred around \$240 billion in annual costs to the U.S. economy over the past decade. The Fourth National Climate Assessment, authored by climate experts from 13 U.S. federal agencies, concluded that the U.S. economy may collapse by as much as 10 percent by the century's end if climate change persists at its current rate. These economic costs stem from extreme weather occurrences, deteriorating air quality, increasing sea levels, and other consequences. Transitioning from fossil fuels to renewable energy sources may mitigate climate change and prevent certain economic detriments.

The advantages of utilising increased renewable energy and diminished fossil fuel are numerous. It is advantageous for the environment and human health, and it also yields numerous good economic effects. Collectively, these advantages present a persuasive case for increased investment in renewable energy sources.

7.0 The Obstacles to Renewable Energy utilisation in Nigeria

Given that high-impact renewable energy can assist Nigeria in lowering emissions at a comparatively low cost while also offering health and employment advantages, what accounts for its limited penetration in Nigeria's energy market? A few of such reasons are listed below:

- a. The configuration of the majority of electrical markets in Nigeria is not favourable for distributed generation, private-sector innovation, or consumer choice. The implementation of high-impact renewable electricity applications remains predominantly at the discretion of regulated monopolies, which possess minimal motivation to pursue such initiatives.
- b. Market inertia strongly favours conventional energy sources due to investor confidence, utility proficiency, market frameworks, and energy distribution infrastructure. Public funding for the research and development of fossil fuels, nuclear, and large hydro resources in Nigeria has significantly surpassed and continues to overshadow support for renewable energy. Despite a current drop, federal assistance for fossil fuels and nuclear power amounted to around \$2.8 billion and \$1.4 billion, respectively, from 1990 to 1999. Eleven
- c. In numerous instances, federal and provincial tax frameworks unintentionally promote the advancement of fossil fuels at the expense of renewable energy sources.
- d. There exists considerable institutional momentum inside the government that persists in favouring old energy sources over renewable alternatives, despite compelling economic, environmental, and health arguments to the contrary.
- e. Substantial market inertia favours conventional energy sources for investor confidence, utility proficiency, market frameworks, and energy distribution infrastructure.

8. PRAGMATIC CLIMATE CHANGE SOLUTIONS FOR NIGERIA

Nigeria is presently encountering difficulties characterised by complex, direct, and indirect impacts, including food insecurity, forced relocations due to flooding, violence, adverse health consequences, and additional factors, which collectively impede climate action and economic development. Droughts and desertification in the dry and semi-arid regions of northern Nigeria have adversely impacted local people reliant on rain-fed agriculture. Droughts and

desertification are causing nomadic pastoral populations to migrate from north to south, leading to conflicts with indigenous agricultural communities over dwindling resources. These nomadic cattle herders also introduce zoonotic infections that may be intensified by climate change (<https://www.iceednigeria.org/resources/nov.-2005.pdf>).

Nigeria must select climate change solutions that not only mitigate GHG emissions but also promote long-term economic stability and overall environmental health. The alternatives recognised by Nigeria's high-impact renewable energy sector align with the following principles:

- a. Avoid Transferring Environmental and Health Burdens - It would be detrimental to Nigerians if we merely transition to energy sources with low greenhouse gas emissions (e.g., massive hydro and nuclear) without considering the comprehensive array of related environmental and health consequences.
- b. Integrate Nigerians into Climate Change Solutions - Strategies must extend beyond industrial focus to also encourage individual Nigerians to engage in proactive measures. If Nigerians are not involved in the solution, consumer attitudes will change gradually, and foundational buying patterns will persist.
- c. Prioritise Reduction (first), Refuelling (second), and Remediation (last) - Our primary objective should be to diminish consumption. Our alternative option should be to replenish with more environmentally friendly energy sources. Implementing end-of-pipe solutions should be our final option. For instance, sequestering CO₂ and injecting it subterraneously may appear to be a viable short-term solution; yet, it is likely to exacerbate Nigeria's economic and environmental responsibilities in the long term.

The high-impact renewable energy sector in Nigeria has identified three primary strategies for mitigating greenhouse gas emissions:

- a. Foster the establishment of a high-impact renewable electricity market.
- b. Promote the adoption of consumer-oriented renewable technologies.
- c. Advocate for increased utilisation of passive renewable energy and energy efficiency measures.

A series of complimentary measures has been formulated for each of these alternatives. Implementation of these steps will enhance our nation's ability to address climate change and diminish future emission reduction costs. These approaches do not entail indefinite subsidies. They concentrate on cultivating a sustainable long-term market for renewable energy and enabling Nigerians to engage in addressing climate change issues.

8.1 Stimulating the Development of a high-Impact Renewable Electricity Market

Approximately 20% of Nigeria's power is generated by the combustion of coal, oil, and natural gas, contributing to roughly 17% of the nation's greenhouse gas emissions. Currently, high-impact renewable energy accounts for less than 1% of Nigeria's electricity supply, despite the country's substantial high-impact renewable resources and considerable potential for emission reduction. In Europe, despite inferior wind resources compared to Nigeria, wind energy generates sufficient power to meet the home electrical requirements of over 5 million individuals. Thirteen The prospective benefits of emission reduction from high-impact renewable electricity extend far beyond the electricity sector. In fossil-fuel intensive industries such as transportation, possibilities exist to mitigate emissions by transitioning from fossil fuels to electricity.

The subsequent strategies aim to cultivate a sustainable market for grid-connected high-impact renewable electricity. The objective of these actions is to initiate a shift in the prevailing market inertia from fossil fuel usage to greener energy sources.

Nigeria is addressing the obstacles to its green energy transition. Approximately 71% of Nigeria's populace lacks access to energy. The Nigerian government intends to attain universal electricity access by 2030. The energy sector encounters significant financial and technical obstacles.

The International Energy Agency reports that over 140 million individuals in Nigeria lack access to energy, constituting around 71% of the nation's population. Energy access pertains to individuals' capacity to obtain modern energy services, encompassing power, clean cooking solutions, and contemporary fuels. Energy inaccessibility adversely affects health, education, and economic development.

Nigeria is Africa's largest economy, endowed with abundant natural resources, particularly oil and gas, and ranks among the world's foremost oil producers. As the nation's economy expands swiftly, its energy need concurrently increases. The Government of Nigeria aims to attain universal energy access by 2030 and is enacting many policies and efforts to enhance access to clean and affordable energy for its populace.

The energy sector confronts numerous issues, such as limited power generation, poor infrastructure, and a significant prevalence of energy poverty. Substantial efforts are underway to diversify energy sources, enhance the nation's energy infrastructure, and tackle difficulties through investments in renewable energy and energy-efficient technologies, while also fostering private sector investments.

Notwithstanding a general rise in worldwide investment in energy transition technologies, Sub-Saharan Africa garnered less than 1.5% from 2000 to 2020. Securing the requisite capital will necessitate vigorous engagement between the government and the private sector, significantly enhancing the probability of Nigeria attaining an equitable transition. Nigeria's energy sources mostly consist of petroleum reserves, natural gas, hydroelectric power, and solar energy. The nation continues to be a leading producer of crude oil and natural gas in Africa. Approximately 45% of Nigeria's population is actively linked to the electrical grid, with a significant concentration in urban regions. Reforms in the power sector have recognised the necessity for development into rural regions, particularly through decentralised renewable energy and enhanced energy efficiency in these areas.

8.2 What are the solutions for Nigeria's energy transition?

The Rural Electrification Agency asserts that enhancing rural electrification via distributed solar production, mini-grids, and off-grid technological solutions could yield \$9.2 billion in annual market investments for solar mini-grids. This may also conserve \$4.4 billion yearly for Nigerian homes and enterprises. Nevertheless, specific obstacles remain in the widespread implementation of solar energy generating.

We cannot advocate for the adoption of renewable energy without informing individuals about its social, economic, and environmental advantages. Africa requires a paradigm transformation, which is unattainable without collaborative engagement among all stakeholders. Significant prospects exist in green energy; nevertheless, the government must mitigate risks to attract investments.

Nigeria is the foremost consumer of oil-fired backup generators in Africa, with more than 80% of power generation derived from gas reserves. Consequently, natural gas continues to be the predominant energy source in forthcoming short-term strategies, notwithstanding the transition to alternative renewable resources. The current appeal of natural gas stems from its low-carbon characteristics, rendering it comparatively "clean" and more economical than oil and coal.

Utilising natural gas as a transitional fuel with a feasible trajectory towards more sustainable solutions might provide around \$18.3 billion in gross value added to the local economy. The potential, along with the global challenges confronting the gas sector, may foster exponential expansion in the nation's internal value chain. Alongside exporting natural gas to the world market, bolstering domestic markets through investments in gas production and local distribution infrastructure is essential for Nigeria's energy transition objectives. The global renewable energy market is substantial and expanding rapidly. Africa must take necessary measures to capitalise on these prospects and bridge the energy gap to prevent a descent into greater poverty. Africa has considerable natural gas, hydroelectric, and solar resources, capable of producing substantial electric power from current facilities. Notwithstanding this capability, the absence of transmission and distribution infrastructure impedes the expansion of both large and small enterprises and has resulted in a significant number of unserved households lacking access to the national grid.

The Nigerian government's implementation of various energy policies and programs over the past decade presents a distinctive opportunity for foreign capital investors to engage in a market rich in energy resources and equipped with a competent workforce. According to the 2022 Nigeria Energy Transition Plan, the government aims to facilitate \$1.9 trillion in energy investments by 2060. This acceleration necessitates comprehensive policy coordination and harmonisation to optimise current and forthcoming government-related energy transition legislation.

Nigeria has recently initiated the Energy Transition Plan aimed at attaining universal energy access by 2030 and establishing a carbon-neutral energy system by 2060; however, an action plan delineating specific targets and timelines is necessary. This will provide effective monitoring of the strategy and the attainment of its objectives. The Power Sector Reform Bill enacted in 2022 in Nigeria permits states, corporate entities, and individuals to engage in power generation, transmission, and distribution. The reform measure was designed to control tariffs for power generation, transmission, and distribution, facilitating energy access by enhancing large-scale generation capacity and transmission and distribution networks.

Furthermore, Nigeria's inflation rate surged by 16 percent in 2022, leading to diminished cash availability and constraining developers' access to funding. The availability of financing for capital costs associated with clean energy projects in dollars is constrained, and currency swings present a risk to overseas investors and project developers. Projects necessitating substantial initial capital investment will gain from a facility that offers access to local currency alongside a mechanism that allows developers to acquire dollars at the naira bank rate. These facilities will facilitate the issuance of corporate infrastructure debt instruments and attract investment from insurance companies, pension funds, and other entities, thereby strengthening Nigerian debt capital markets by mitigating overall credit risk and reducing capital costs for developers, while safeguarding conservative capital from potential losses. This will provide enhanced flexibility to developers, enabling them to finance their projects in local currency.

Nigeria acknowledges the essential requirement for technical capacity enhancement via

accelerator programs for solar entrepreneurs and developers as it endeavours to reform its energy sector. Numerous major and small-scale clean energy initiatives depend on foreign expertise for technical support and financial guidance.

Training is now administered by official entities, including the Rural Electrification Agency (REA) and the Renewable Energy Association of Nigeria (REAN), while technical support is sporadically offered by Development Finance Institutions (DFIs) and foundations. It is essential to cultivate this talent domestically and guarantee the long-term development of local expertise.

The solutions identified in the Deep Dive tackle the financial obstacles in Nigeria's clean energy priority sectors and facilitate the investments required to advance Nigeria's energy objectives.

8.3 Measure A) Consumer Information on Electricity Products

This regulation mandates the compulsory disclosure of information regarding generation sources and emissions attributes by electricity wholesalers. There is a necessity for an Electric Power Content Label. This pertains to a document or system that reveals the sources of electricity generation utilised to supply power to the grid. It resembles a nutrition label on food, offering clarity regarding the energy composition. A Power Content Label (PCL) or Electricity Content Label conveys details regarding the various energy sources (such as natural gas, hydropower, or renewables) utilised in the generation of electricity supplied to the power grid. This label intends to inform users with the composition of their electrical supply. It enables users to comprehend the ecological consequences of their electricity usage.

PCLs are significant as they enhance openness in the electricity market, enabling consumers to make educated decisions regarding their energy consumption. Informed Choices (By understanding energy sources, consumers can selectively support or diminish their electricity consumption from particular sources, such as renewable energy), Environmental Awareness (The label can indicate the percentage of renewable energy in the mix, fostering awareness of sustainable energy practices). The Federal Ministry of Power is the governmental entity accountable for the power sector in Nigeria. The Nigerian power Regulatory Commission (NERC) serves as the autonomous regulatory authority for the power supply sector in Nigeria. Information regarding power generation and other data may be found on their website. Electricity Distribution Corporations (DisCos). The local distribution company (e.g., Kaduna Electric) may additionally furnish information regarding the electricity they distribute. The Federal Ministry of Power's website offers daily updates on electricity generation, encompassing peak and off-peak statistics, frequency, and total energy produced and distributed. This information, although not formally offered as a PCL, enhances the comprehensive understanding of Nigeria's energy supply.

Information regarding electrical products would enable Nigerians to comprehend the effects of electricity generating and equip them to make informed decisions regarding their consumption levels and types of electricity. The compulsory uniform labelling of electrical products in Nigeria, especially for appliances such as air conditioners and refrigerators, seeks to enhance energy efficiency. The Standards Organisation of Nigeria (SON) has launched a national energy efficiency label, often known as the Energy Guide Label, to assist customers in making informed purchase decisions on energy use and efficiency. This label conveys details regarding the product's energy consumption, cooling capacity (for air conditioners), and a rating system (such as the A-G scale) that signifies energy efficiency. The objective is to promote the adoption of more energy-efficient equipment, resulting in decreased electricity expenses and

overall energy usage. These labels are essential for educating consumers regarding the energy efficiency of electrical equipment. The Energy Guide Label assists consumers in comprehending the energy consumption of a particular appliance and its comparison to other market options.

Minimum Energy Performance Standards (MEPS) are criteria for energy efficiency that items must satisfy to be marketed. The Nigerian government has sanctioned new Minimum Energy Performance Standards (MEPS) for air conditioners to guarantee that only efficient models are marketed. The enforcement of these labels and standards frequently necessitates obligatory adherence for producers and importers of electrical products. SON is expected to implement these requirements to guarantee that products comply with the requisite standards.

The use of energy efficiency labels and standards offers numerous advantages, including:

- 1) *Decreased energy consumption:* Consumers can make informed decisions on more efficient equipment, resulting in diminished electricity expenses and alleviated pressure on the power grid.
- 2) *Environmental protection:* Decreased energy usage results in a diminished carbon footprint and a reduction in greenhouse gas emissions.
- 3) *Market transformation:* Promotes manufacturers' investment in energy-efficient technology and designs.
- 4) *Enforcement:* The effective implementation of energy efficiency requirements and labelling is crucial. This includes market surveillance, product testing, and sanctions for non-compliance.
- 5) *Regulatory Bodies:* The Nigerian Electricity Regulatory Commission (NERC) oversees the regulation of the electricity sector, while the Nigerian Electricity Management Services Agency (NEMSA) enforces technical standards and regulations pertaining to electrical installations and equipment.

Mandatory standard labelling for electrical devices must be developed, since other countries, notably the U.S., Canada, and China, have already implemented such measures. Nigeria now has the Comprehensive Electricity Competition Act, referred to as the Electricity Act 2023. This Nigerian legislation aims to restructure the power sector by establishing a more competitive and privately-driven market. It abrogates the Electric Power Sector Reform Act of 2005 and seeks to encourage investment, boost efficiency, and bolster consumer protection. The Act's principal objective is to create a framework for a privatised, contract-based, and regulation-driven competitive electricity market in Nigeria. The Act's key features encompass Decentralisation (empowering states, companies, and individuals to generate, transmit, and distribute electricity), Private Sector Involvement (promoting private sector participation throughout the electricity value chain), Regulatory Framework (establishing a comprehensive legal and institutional framework for the Nigerian Electricity Supply Industry), Renewable Energy (incentivising renewable energy initiatives), and Consumer Protection (incorporating provisions for consumer safeguarding). The Act is anticipated to stimulate investment, augment efficiency, and elevate competition within the power industry. The Act abrogates the Electric Power Sector Reform Act of 2005. The Electricity Act 2023 effectively reinstates state control in the power sector to levels prior to 1999.

8.4 GHG Impact

While quantifying the resultant reductions is challenging, this measure is an essential foundation for establishing a renewable electricity market.

8.5 Costs and Implementation

The expenses are minimal and may be covered by the government, utility companies, or customers. Their nature is administrative, involving the monitoring of power supply by generation source and modifying billing systems to integrate generation data. In numerous countries, these administrative functionalities are already established. While consumer protection legislation and utility regulation fall under provincial jurisdiction, the federal government may seek to initiate and standardise disclosure rules nationwide to maintain uniformity. Labelling regulations may be established by an industry association or by regulatory agencies inside the country.

8.6 Measure B) Market-Wide Incentives for High-Impact Renewable Generation

This measure identifies three possible market-wide incentives to increase the proportion of high-Impact renewable electricity in Nigeria's generation mix. They are:

- a) a green power consumer rebate or credit;
- b) a high-Impact renewable production rebate or credit; and
- c) a high-Impact renewable portfolio standard.

8.7 Green power consumer rebate or credit

In Nigeria, while there aren't specific consumer rebates or credits for green power directly, the government offers tax incentives and other measures to encourage renewable energy adoption. This includes VAT exemptions on renewable energy equipment and potential power production tax credits for individuals generating electricity from renewable sources.

Tax Incentives include VAT Exemptions (The VAT (Modification) Order 2021 provides a VAT exemption for renewable energy equipment, including solar panels, wind turbines, and off-grid power systems. This also applies to green electricity supplied to the national grid), Power Production Tax Credit (PPTC), The National Renewable Energy and Energy Efficiency Policy (NREEEP) propose a PPTC to incentivize individuals who generate electricity from renewable energy. The Nigerian government is also considering other fiscal incentives to spur investment and innovation in the renewable energy sector.

Other Support Mechanisms include Rural Electrification Fund (REF) (The REF supports the expansion of the grid and the development of off-grid electrification, including renewable energy projects. Renewable Energy Master Plan (REMP) (This plan aims to increase the share of renewable electricity in Nigeria's energy mix, Private Sector Involvement (The government is encouraging private sector participation in renewable energy development, including initiatives like the Distributed Renewable Energy Nigeria Fund.

It should be noted that while the government is taking steps to promote renewable energy, there are challenges in implementing these policies and ensuring consistent application of incentives. The lack of clear operational processes for obtaining and renewing some incentives is a concern. Despite these challenges, Nigeria has significant potential for renewable energy, particularly solar and hydro, and the government is working to unlock this potential. Because of Nigeria's diverse political and economic landscape, one of these incentives may be more suited to a particular region than the others. In general, the goal should be to have one of these incentives implemented in each Region.

8.8 High-Impact renewable production rebate or credit

In Nigeria, while there aren't specific consumer rebates or credits for green power like solar

panels, the government is actively promoting renewable energy through various incentives. These include tax breaks for renewable energy companies, import duty waivers on equipment, and a VAT exemption on renewable energy equipment and green electricity supplied to the grid. Incentives for Renewable Energy in Nigeria include Tax Holidays (Businesses involved in renewable energy production can benefit from tax holidays of up to five years), Import Duty Waivers (There are waivers on import duties for renewable energy equipment like solar panels, batteries, and inverters), VAT Exemption (The VAT (Modification) Order 2021 exempts renewable energy equipment and green electricity from the standard 7.5% VAT rate), Power Production Tax Credit (PPTC) (The National Renewable Energy and Energy Efficiency Policy (NREEEP) proposes a PPTC to incentivize individuals generating electricity from renewable sources), Rural Electrification Fund (REF) (The REF supports investors and stimulates innovative approaches to rural electrification, including the development of off-grid solutions), Fidelity Green Energy Finance (This initiative by Fidelity Bank provides funding options for renewable energy solutions like solar systems, inverters, and batteries for homes and SMEs), Distributed Renewable Energy Nigeria Fund.

The focus on incentives for businesses and projects rather than direct consumer rebates is likely due to the early stage of development of the renewable energy market in Nigeria. The government is prioritizing attracting investment and developing the infrastructure needed to support widespread renewable energy adoption. While direct consumer incentives are not yet widespread, the government's commitment to renewable energy development suggests that these may become more common as the sector matures.

GHG Impact (2.3 Mt)

This measure assumes that for each of the three possible incentives, the net benefit to high-Impact renewable electricity generators is a reduction in production costs of 2.5 cents/kWh. Analysis by the National Climate Change Process Electricity Issues Table indicates this would result in GHG reductions of 2.3 Mt a year by 2010.

Costs and Implementation

For each of the three possible incentives, the costs could be shared between the federal government and, depending on the incentive, either provincial governments or Nigerian consumers. If the federal government were to provide the full amount of the incentive, modelling by the National Electricity Table indicates the cost would be approximately \$60 million per year. Implementation would differ depending on the incentive chosen.

The three incentives are described in more detail below.

1) Green Power Consumer Credit

This measure requires the federal government to provide a rebate or tax credit to those electricity consumers who purchase power generated by certified high-Impact renewable energy sources. This not only helps stimulate the market for renewables, but also empowers Nigerians to participate in the solution to climate change through their purchasing power.

Consumers in California have responded positively to a customer credit program of this nature. In California, of the 1% who have switched service providers since deregulation, approximately half purchased a renewable energy product. In Pennsylvania, it is estimated that almost 10% of the state's residents have switched to a new service provider, and 20% of those have selected a green power product. 14 Green marketers in the U.S. expect to garner 0.5%-2% of the residential market in the first year of deregulation and 4%-5% after five years.

Nigeria has two green power programs offered by the Calgary (ENMAX) and Edmonton (Edmonton Power) electric systems who are preparing for electricity deregulation in Alberta in 2001. In the first three months of the Calgary program more than 1000 customers signed on to purchase wind power.

A cost-sharing arrangement for this incentive might see the federal government provide a 1.5 cent/kWh credit, while consumers cover the additional 1.0 cent/kWh premium. A 1.0 cent/kWh premium represents an increase of about \$5-\$10 per month for the average Nigerian household, if all its electricity came from low impact renewable sources. If this incentive is implemented across Nigeria, it requires the participation of only 3% of residential consumers and 2% of commercial consumers to achieve the full 2.3 Mt of reductions. This measure requires that Nigerian consumers have the option to buy high-Impact renewable electricity in either deregulated or regulated markets.

2) high-Impact Renewable Production Credit

This incentive provides high-Impact renewable electricity generators with a credit proportional to their output. It could be delivered as a tax credit or outside the tax system as a rebate, depending on the extent of the producer's taxability. The benefits of this incentive are that it is administratively simple and encourages operating efficiency. The U.S. has offered several tax incentives for high-Impact renewable energy over the last two decades, well beyond the accelerated depreciation offered in Nigeria. Most notable is the 10-year, 1.5 cent/kWh production tax credit implemented in 1992 to encourage wind energy development. The cost of this measure would likely be shared between the federal and provincial governments, as it would mean new economic activity, employment and tax revenues within a province.

3)Renewable Portfolio Standard

A renewable portfolio standard requires a certain percentage of electricity sold in a province to be generated from renewable energy. This quota approach would have a significant effect on emissions and dramatically accelerate the commercialization of emerging technologies. In order to limit costs, a system of tradeable "renewable energy credits" could be developed to allow retailers to purchase reductions from least-cost sources anywhere in Nigeria. In addition, the program could be terminated at a fixed point in the future. An RPS could be implemented in either regulated or deregulated electricity markets.

In order to achieve a reduction of 2.3 Mt of GHG emissions, every province would have to receive approximately 1% of its electricity from high-Impact renewable sources. The U.S. Administration has proposed an RPS of 7.5% for all electricity retailers between 2010-2015, and other bills in the U.S. House and Senate propose quotas of 10-20%.

The federal government could share the additional costs of an RPS with either the provincial governments or Nigerian consumers. This, however, is not consistent with the existing or proposed programs in the U.S. and Europe, which involve little cost to government. The quota is simply mandated and consumers pay the additional cost. These additional costs are not large because they are shared so widely. Because of their jurisdiction over electricity regulation, provincial governments would be responsible for establishing renewable portfolio standards. However, if there were a system of nationwide tradeable RPS credits, it would require coordination between provincial governments on a national scale.

8.9 Measure C) Government Green Power Procurement

This measure would see federal, provincial and municipal governments make a commitment to buy a portion of their electricity from renewable energy sources. A similar measure has received general support at the National Climate Change Process Electricity Issue Table. In 1994, the federal government's Task Force on Economic Instruments and Disincentives to Sound Environmental Practices recommended the government purchase a specific percentage of its electricity (15-20%) from "green power" sources. By doing so, the Task Force suggested, the government would demonstrate leadership, reduce the impact of its operations, and support the development of renewable energy. So far, two federal departments, Natural Resources Nigeria and Environment Nigeria, have taken up the challenge by pledging to buy between 15% and 20% of their electricity from renewables by 2010. The purchase of green power by these two departments for their Alberta facilities has helped stimulate the initial market for renewables in the province. However, in order for Nigerian governments to encourage a stable market for renewables and accelerate cost reductions, a more significant commitment is required.

GHG Impact (0.4 Mt)

If the federal government alone were to purchase 15% of its total electricity supply from high-Impact renewable sources by the year 2010, it would result in reductions of 0.4 Mt¹⁵. If provincial and municipal governments did the same, the reduction in emissions would more than double.

Costs and Implementation

The additional cost to the federal government for purchasing 15% of its power from green sources (assuming a 2.5 cent/kWh premium for renewable electricity) would be \$11.2 million per year for 10 years.

8.10 Measure D) Remove the Effect of Tax-Induced Barriers to Renewable Energy

Currently, fossil-fuel based companies and their investors enjoy greater access to federally-legislated tax write-offs than high-Impact renewable energy companies. As a result, companies that explore, develop and use fossil-fuels are encouraged by the tax system to make the necessary investments to grow while high-Impact renewable energy companies are not. The two underlying causes for this incentive to pollute are: 1) the existing tax write-offs for renewable energy companies are "trapped" and cannot be used to the same extent as the write-offs available to their fossil-fuel counterparts; and 2) the tax system treats capital and operating costs differently, and because renewable energy companies have a higher proportion of capital costs than their fossil-fuel counterparts, their proportional tax write-offs are smaller.

This measure proposes the federal government eliminate the effect of tax-induced barriers to the development of high-Impact renewable energy. Regardless of how this is achieved, this oversight in the tax system requires a resolution or it will continue to significantly disadvantage high-Impact renewable energy companies and limit Nigeria's ability to reduce emissions.

This issue has been identified by the National Climate Change Process Electricity Issue Table, and the Nigerian Electricity and Nigerian Gas Associations in their 1999 federal budget submissions. All of these groups recommended that the issue be addressed immediately.

GHG Impact (1.4 Mt)

Industry experts estimate that removing federal tax barriers to renewable energy will reduce costs by 1.5 to 2 cents/kWh.¹⁶ In analysis by the National Climate Change Process Electricity

Issue Table, a cost reduction of 1.5 cents/kWh for renewable energy resulted in 1.4 Mt of reductions.

Costs and Implementation

The cost of this measure is unknown. However, it is arguable that the additional new tax revenues resulting from growth in an emerging industry would outweigh the lost tax revenues. The federal government needs to sit down with industry stakeholders to find a solution that both removes the tax barriers and maintains the integrity of the tax system.

8.11 Support Consumer-Based Renewable Technology

Use Greenhouse gas emissions from the residential and commercial sectors represent approximately 10% of Nigeria's total. These result from using fossil fuels directly for space and water heating, as well as fossil-fuel-generated electricity for lighting, cooking, heating and appliances. Greenhouse gas emissions from passenger transportation represent approximately 15% of Nigeria's total. In many aspects of residential, commercial and agricultural energy use, there are significant opportunities to reduce emissions through the use of renewable technologies such as solar panels, solar hot water heaters, wind generators, ground-source heat pumps and biofuels. The following measures identify opportunities to increase the use of high-Impact renewable energy technologies by Nigerian consumers and companies, allowing them to participate directly in the solutions to climate change.

8.11.1 Measure A) Net Metering

Net metering involves giving credit to electricity consumers whenever their on-site generation from solar, micro-hydro or wind exceeds their electricity use. Credit is given to consumers by reversing the direction of their electricity meter and crediting them the same price for the electricity they feed onto the grid as they pay for the power they take from the grid. This measure has been explored by the National Climate Change Process Electricity Issue Table.

At least 26 states in the U.S. have adopted net metering and the U.S. Administration's proposed electricity act would require it in all states. Japan and Germany have net metering nationally. Ontario Power Generation and Toronto Hydro currently have net metering pilot programs underway. This measure provides an economic incentive for Nigerians to invest in renewable technologies without requiring government funding.

8.11.2 GHG Impact (0.1 Mt)

Based on the average level of customer uptake in existing net metering pilot programs in the U.S. and Nigeria, it is estimated that net metering would result in enough on-site renewable systems to provide electricity to approximately 30,000 Nigerian homes. Assuming these systems are installed in those provinces with the best renewable energy regimes, it would result in 0.1 Mt of reductions.¹⁷

8.11.3 Costs and Implementation

The cost of purchasing renewable energy equipment and connecting to the grid is paid for by the customer. In general, the cost to the electricity provider is small, but depends on the characteristics of the renewable energy source and customer. This measure requires that all retailers of electricity offer a net metering tariff to their customers. This will have to be regulated by provincial governments, with reasonable connection requirements regarding safety, technology specifications, and liability.

8.12 Measure B) Consumer Credit for Agricultural Renewable Electricity Generation

This measure provides a rebate or credit to rural electricity consumers for their on-site renewable generation. This measure complements net metering by further decreasing the payback time for on-site renewable technologies such as wind turbines, solar PV and micro-hydro. Like many of the other measures identified, this measure empowers Nigerians to participate in the solutions to climate change and allows them to take responsibility for the impact of their own consumption.

8.12.1 GHG Impact (0.5 Mt)

For example, if farmers received a 1.5 cent/kWh rebate or credit for small-scale wind generation, it would decrease the payback time on the average wind generator by 30%. This translates into a payback period of less than 15 years for a 50-kW turbine and less than 10 years for a 10-kW turbine. Assuming this resulted in 5% of Nigerian farmers (or 7% of farms in Alberta, Saskatchewan and Ontario) installing wind generators, 0.5 Mt of reductions would occur.

8.12.2 Costs and Implementation

For the GHG reduction stated above, the cost to government of this measure is roughly \$11 million per year for 10 years. This measure requires net metering and involves a partnership between the federal government, electricity suppliers and Nigerians living in rural areas. It could be administered as either a rebate through the electricity supplier or as a credit through the federal income tax system.

8.13 Measure C) Federal Government and Municipalities 50,000 Solar Roofs Partnership

This measure involves a partnership between the Nigerian government, municipalities and large commercial electricity consumers. The goal is to have 50,000 large solar PV systems installed on municipal and commercial buildings across Nigeria by 2010. Large-volume electricity consumers benefit by cutting down their peak load when electricity is most expensive (often reaching 25 cents/kWh). This volume of solar installations would drive cost reductions in solar PV technology and create significant Nigerian expertise and employment in an industry that is growing rapidly worldwide.

8.13.1 GHG Impact (0.4 Mt)

If the federal government provided a 3 cent/kWh credit to those municipalities and commercial consumers that install large solar systems, it would reduce the payback period to under 25 years. If 50,000 systems were installed by 2010, it would result in 0.4 Mt of reductions¹⁸.

8.13.2 Costs and Implementation

The cost to the federal government for this measure would be roughly \$17 million per year for 10 years. It requires the federal government to work with municipalities and businesses to identify the lowest-cost opportunities for solar systems.

8.14 Measure D) Accelerated Financing for Space and Water Heating Renewable Technologies

This measure helps Nigerian consumers reduce the burden of capitalization when they choose to purchase a renewable technology for space or water heating purposes, such as a solar hot water or a ground-source heat pump. The federal government would guarantee fixed financing rates for purchases of specified small-scale solar and earth energy technologies. These technologies are also practical on a larger scale and a similar measure could be implemented for commercial and public buildings.

8.14.1 GHG Impact (2.0 Mt)

For example, if the government offered guaranteed financing at 7% on a 10-year loan for the purchase of specified renewable systems, it would change the current costs from a simple payback of 7 years into a net reduction of monthly energy costs from day one. Based on predictions by Natural Resources Nigeria, this would result in at least 8% of Nigerian homes, or 660,000 households, installing Solar Domestic Hot Water, with a resulting reduction in emissions of approximately 2.0 Mt¹⁹.

8.14.2 Costs and Implementation

Based on the GHG impact described above and assuming that 10-year lending rates average 9% between 2000-2010, the cost to government of the 2% spread would be approximately \$16 million per year for 10 years. Implementation of this measure would be similar to the initiative administered under the Small Business Loans Act, involving both the federal government and private-sector lenders.

8.15 Measure E) Minimum Biomass Fuel Content in Gasoline

This measure would see the federal government mandate that gasoline sold for transportation purposes contain a minimum percentage of biofuels. Biofuels, such as ethanol, are produced from a variety of agricultural crops as well as wood and agricultural wastes. Although combustion of biofuels does produce greenhouse gases, they are significantly less carbon intensive than gasoline. Despite the fact that Nigeria is a world leader in the production of agricultural and forest fibre products, we are not one of the world's top 10 biomass fuel producers. It is estimated that Nigeria currently produces less than 5% of the country's readily available biomass fuel resources.²⁰

8.15.1 GHG Impact (3.1 Mt)

If the federal government were to mandate that all gasoline used for transportation contain 5% biomass fuel by 2010, it would result in annual greenhouse gas reductions of 3.1 Mt from projected levels.²¹

8.15.2 Costs and Implementation

The cost to government of this measure alone would be small but would likely need to be complemented with other measures such as tax breaks for biomass fuels and loan guarantees for construction of biomass fuel production facilities in order to achieve the proposed 5% target by 2010. The federal government currently provides an excise tax exemption for alternative transportation fuels and has provided some loan guarantees to ethanol producers. It is arguable that a continuation of the excise tax exemption would be revenue neutral or net positive for the government as a result of new economic activity created by the biomass fuel industry.

Nigeria's transportation sector is responsible for 27% of our GHG emissions. Cars and light-duty trucks are the single biggest contributor to these emissions.³.

9. ENCOURAGE GREATER PASSIVE RENEWABLE AND ENERGY EFFICIENCY USE

More than half of all homes in Nigeria were built before 1980. Since then, many cost-effective technologies have been developed to significantly improve the energy efficiency of older buildings. In addition, new building techniques and technologies have been developed in the residential sector that significantly increase the passive use of solar energy and energy efficiency over what is achieved by most of the houses built today. As a result, the potential to reduce greenhouse gas emissions through energy-efficient retrofits and new building

techniques is considerable.

The following measures would encourage significant improvements in the use of passive solar and energy efficiency techniques in both existing and new Nigerian homes. Again, this measure would allow Nigerians to participate directly in the solutions to climate change while helping to change long-term energy consumption patterns.

9.1 Measure A) Reduced Financing Costs for R-2000 Homes

This measure would see the federal government guarantee preferred mortgage rates for Nigerians who choose to build R-2000 homes. A measure to strengthen Nigeria's R-2000 Program has also been discussed by the National Climate Change Process Buildings Issue Table.

Natural Resources Nigeria estimates that a new home built to R-2000 standards would reduce energy use by 26% relative to the average new home built in 1994.²² Because R-2000 homes are slightly more expensive than conventional housing, however, those who choose to minimize their impact on the environment must take on a larger financial burden, both in terms of debt and property taxes. By removing this disincentive to save energy, the government would not only empower Nigerians to reduce emissions, but also decrease the future cost of energy-efficient housing through the widespread adoption of R-2000 building methods. The Yukon Housing Corporation supports this concept through its recent initiative to provide a 1% reduction in mortgage rates for new homes or renovations that rate 80 on the Nigerian Energuide Scale.

9.1.1 GHG Impact (0.5 Mt)

If the government were to guarantee a 0.5% reduction on 5-year mortgage rates it would save the new R-2000 home owner approximately \$4,000 and reduce the length of his or her mortgage by roughly two years.²³ If this resulted in 15% of all new homes being built to R-2000 standards, GHG emissions would be reduced by 0.5 Mt relative to projected levels for 2010.²⁴ If provincial governments were to mandate the R-2000 standard as the building code for all new homes constructed after the year 2000, it would result in 3.7 Mt of GHG reductions by the year 2010.²⁵

9.1.2 Costs and Implementation

The federal government would need to work in cooperation with the financial community to provide preferred mortgage rates. Assuming the federal government could establish the necessary partnerships with lending institutions, the cost of implementing this measure would be small.

9.2 Measure B) Incentives for Residential Energy Efficient Retrofits

This measure involves a combination of incentives to encourage energy-efficient retrofits in residential buildings. These incentives should include improved access to financing and tax breaks for homeowners who invest in energy-efficient retrofits. The National Climate Change Process Buildings Issue Table has discussed a similar measure.

9.2.1 GHG Impact (1.4 Mt)

If, by the year 2010, the above incentives resulted in 25% of existing Nigerian homes improving their energy efficiency by 20%, it would result in 1.4 Mt of GHG reductions.²⁶

9.2.2 Costs and Implementation

If the costs of this measure were shared evenly with provincial governments, the cost to the

federal government would be in the order of \$27 million per year.²⁷ The measure would involve an expansion of NRCan's residential energy efficiency program and require the federal government to establish partnerships with financial institutions and Nigerian homeowners.

10. CONCLUSION

The analysis in this paper and preliminary analysis carried out through the National Climate Change Process indicates, without a doubt, that existing high-Impact renewable energy technologies can make a significant contribution to Nigeria's greenhouse gas reduction targets over the next ten years. The estimates of potential GHG reductions achieved by the measures proposed in this paper are conservative. By 2030, the spin-off actions caused by these measures would likely result in reductions far greater than the estimated 8% of Nigeria's reduction target. By 2020, the dividends would likely double. In addition, the development of high-Impact renewable energy resources would create thousands of additional jobs and result in a considerable reduction in health care costs.

The cost of high-Impact renewable technologies has dropped dramatically in the last decade and continues to drop as industrialized nations and multinationals invest heavily in their development. In fact, some high-Impact renewable technologies are close to achieving price equity with fossil-fuel based technologies without even taking into account their environmental and health benefits. Nigeria has the opportunity to prosper in a renewable energy future. Our country has some of the world's best high-Impact renewable energy resources and a proud history in energy resource development. We must act now to develop a strong domestic market for high-Impact renewable energy. This will significantly reduce Nigeria's economic and environmental liabilities and help keep our nation competitive in the rapidly changing global energy market.

The political, economic and environmental events of the last decade clearly indicate that nations around the world are choosing a path towards cleaner energy sources and healthier economies. Nigeria's high-Impact renewable energy industries call on Nigerians and Nigerian governments to do the same.

The strategies outlined in this paper constitute an investment in Nigeria's future. If promptly and well executed, they will diminish yearly greenhouse gas (GHG) emissions by over 12 million tonnes (Mt) by 2010 (about 8% of Nigeria's reduction objective), provide thousands of new employment opportunities, and lower healthcare expenditures by millions of dollars annually. The most substantial benefits from these initiatives will manifest post-2035, stemming from the initiation of fundamental shifts in the attitudes of Nigerians and the characteristics of the Nigerian energy market. By 2030, the spin-off actions initiated by these steps are expected to yield greenhouse gas reductions double those attained in 2020.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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CLIMATE CHANGE AND FOOD SECURITY: MULTIDIMENSIONAL IMPACTS, SYSTEMIC VULNERABILITIES AND INTEGRATED ADAPTATION STRATEGIES

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Abstract

Climate change poses escalating and multidimensional threats to global food security, disproportionately affecting vulnerable populations whose livelihoods depend on climate-sensitive agricultural systems. Despite global food production being theoretically sufficient to feed the world's population, nearly 800 million people remain chronically undernourished, while climate-induced disruptions increasingly undermine access, availability, utilisation, and stability—the four foundational pillars of food security. Smallholder farmers, pastoralists, fishers, and forest-dependent communities in low-latitude and resource-constrained regions face heightened exposure to droughts, floods, extreme weather events, and biophysical changes that reduce yields, degrade ecosystems, alter species distributions, destabilise markets, and amplify price volatility. Drawing from contemporary IPCC assessments, FAO analyses, and interdisciplinary scientific evidence, this paper examines the cascading effects of climate change on agricultural productivity, natural resource systems, trade dynamics, nutrition, and rural livelihoods.

The paper identifies the mechanisms through which climate stressors propagate across food systems and synthesises a comprehensive portfolio of adaptation responses. These include social protection measures, climate-resilient agricultural practices, improved water and land management, sustainable fisheries and forest management, strategic investments in agricultural development, genetic resource conservation, institutional strengthening, and enhanced multilevel governance. Emphasis is placed on gender-sensitive, inclusive, and multi-sectoral approaches that integrate risk management, capacity building, and long-term planning. The analysis underscores the urgent need for coordinated national, regional, and global action to safeguard food systems, support vulnerable populations, and achieve zero

hunger in a changing climate. Immediate investment and policy engagement are critical not only to protect current food security but to maintain the future viability of agriculture and nutrition under rising climatic uncertainty.

1. INTRODUCTION

Although enough food is produced globally, about 800 million people remain hungry, indicating that production alone is insufficient (FAO, 2015). Ensuring stable access to adequate and quality food is essential. In 2015, the United Nations reported 836 million people living in extreme poverty (United Nations, 2015). According to the International Fund for Agricultural Development, about 70% of the extremely poor live in rural areas, heavily dependent on agriculture (IFAD, 2015). Around 500 million smallholder farms support nearly 2 billion people, producing up to 80% of the food consumed in Asia and sub-Saharan Africa (FAO, 2014).

Approximately 161 million children under five are affected by stunting (UNICEF, WHO, & World Bank, 2015). Simultaneously, 500 million individuals are classified as obese, while two billion are deficient in essential micronutrients (FAO, IFAD, & WFP, 2015). The FAO projects that global food production must increase by 60% by 2050 (FAO, 2013).

Food security is achieved when “all people, at all times, have physical and economic access to sufficient, safe and nutritious food” (World Food Summit, 1996). This concept comprises four pillars: availability, access, utilisation, and stability (FAO, 2008).

It is insufficient to only produce adequate food globally to satisfy demand; although sufficient food is already produced, about 800 million individuals remain hungry. It is essential that everyone has consistent access to food in appropriate amount and quality. In 2015, the United Nations reported 836 million people living in extreme poverty (United Nations, 2015). According to the International Fund for Agricultural Development, about 70% of the extremely poor live in rural areas, heavily dependent on agriculture (IFAD, 2015). Around 500 million smallholder farms support nearly 2 billion people, producing up to 80% of the food consumed in Asia and sub-Saharan Africa (FAO, 2014).

Climate change threatens progress made against hunger and malnutrition. The IPCC reports that climate change increases risks for food security, especially among vulnerable populations (IPCC, 2014). Four of the eight key climate-related risks directly affect food security:

- a. Loss of rural livelihoods and income,
- b. Degradation of coastal and marine ecosystems,
- c. Degradation of terrestrial ecosystems,
- d. Food insecurity and food system collapse (IPCC, 2014).

The most vulnerable countries—arid regions, landlocked states, and small island developing states—are impacted first and most strongly (IPCC, 2014). Climate change affects trade, markets, and price stability, creating broader food-system challenges (FAO, 2016).

The objective of this paper is to do the following; First, it is imperative to highlight that climate change is currently affecting the food security and nutrition of the most vulnerable populations, and that without prompt action, it will increasingly jeopardise the objective of eradicating hunger. This serves as an additional impetus for governments to undertake ambitious measures to address climate change across all sectors. Secondly, to delineate the specific mechanisms via which climate change ultimately affects food security and to illustrate the spectrum of

necessary solutions. Comprehending these paths and the possible remedies, encompassing both technological measures and social protection as well as enhanced international collaboration, is essential. It underpins the FAO's efforts to eliminate hunger and malnutrition. Third, it seeks to stimulate continuing discussions regarding the implementation of climate change adaptation and to emphasise that food security, nutrition, and the agricultural sectors that underpin them must be prioritised for intervention. Consequently, it seeks to address the adaptation requirements and requests articulated by numerous countries in their Intended Nationally Determined Contributions for COP21.

This paper consolidates material from the IPCC, augmented by recent scientific discoveries and informed by the FAO's practical knowledge and experiences. It offers a comprehensive examination of the cascading effects of climate change on food security and nutrition, encompassing physical consequences on agro-ecosystems, livelihoods, and food security. It elucidates the manner in which the cascade of effects influences a range of vulnerabilities. It outlines strategies to adapt and enhance resilience to climate change to guarantee food security and nutrition. It underscores the necessity of immediate action on climate change: to eradicate hunger and to facilitate the adaptation of agricultural sectors to climate change. It also emphasises the imperative to mitigate climate change to maintain levels that provide and protect universal food security and nutrition.

2. RISKS: IMPACTS OF CLIMATE CHANGE ON FOOD SECURITY - SUMMARY OF CURRENT KNOWLEDGE

The most recent IPCC report corroborates the principal conclusions of earlier IPCC assessments about climate evolution and its primary physical impacts, including alterations in land and ocean temperatures, sea level rise, and ocean acidification. It also enhances comprehension of anticipated spatial alterations in precipitation, including intensity and seasonal distribution. Furthermore, advancements in modelling and data collecting enhance our ability to refine forecasts of climate change impacts in the medium term and at localised levels. These enhancements are vital for comprehending and forecasting future effects on agricultural systems.

Climate change creates significant uncertainties over future water availability in numerous locations. It will influence precipitation, runoff, and snow/ice melt, impacting hydrological systems, water quality, water temperature, and groundwater recharge. In numerous global places, heightened water shortages due to climate change will provide a significant barrier for climate adaptation. Rising sea levels will impact the salinity of both surface and groundwater in coastal regions.

Climate change is expected to influence the occurrence and severity of extreme occurrences. The influence of extreme occurrences on agriculture is already significant. The FAO's recent analysis of 78 post-disaster needs assessments across 48 developing nations from 2003 to 2013 indicates that 25 percent of all economic losses and damages caused by medium- and large-scale climate hazards, including droughts, floods, and storms, impact the agricultural sector in these countries.

Climate change is significantly altering the circumstances for agricultural practices. Climate change exerts both direct and indirect effects on agricultural production systems. Direct affects encompass consequences resulting from alterations in physical qualities, such as temperature. Levels and precipitation distribution in particular agricultural production systems. Indirect effects influence production by altering the dynamics of other species, including

pollinators, pests, disease vectors, and invasive species. These indirect impacts can significantly influence outcomes. They are far more challenging to evaluate and forecast due to the numerous interacting elements and connections, many of which remain unidentified. The anticipated effects of climate change on significant agricultural yields are now thoroughly established, grounded in two decades of research. Globally, adverse effects are more prevalent than beneficial ones. Observations about the impact of climate trends on agricultural output reveal that climate change has adversely influenced wheat and maize yields in numerous places and on a global scale.

Results from significant agricultural model inter-comparison projects indicate that, despite ongoing uncertainties regarding the models' representation of combined carbon dioxide fertilisation, ozone stress, and high temperature effects, there is consensus on the trend of yield changes across numerous major agricultural regions at both low and high latitudes, with pronounced negative impacts particularly at elevated warming levels and in low latitude areas. The IPCC has indicated strong confidence that climate change will consistently and adversely impact crop output in low-latitude countries, although its effects in northern latitudes may be either beneficial or detrimental. While certain high-latitude areas may become more suitable for agriculture, soil quality and water availability could limit sustainable improvements in agricultural productivity in these places. A recent multi-model study utilising the IPCC's most extreme warming scenario revealed a mean yield reduction of 17 percent globally by 2050 for four crop groups (coarse grains, oilseeds, wheat, and rice), which collectively represent approximately 70 percent of the global harvested crop area, compared to a scenario with a stable climate. The hypothesis for this multi-model assessment integrated the most severe radiative forcing scenario with an assumption of constrained CO₂ fertilisation effects in 2050, yet it did not account for the detrimental impacts of elevated ozone concentrations and biotic stresses from various pests and diseases, nor the probability of heightened occurrences of extreme events. Post-2050, the likelihood of exacerbated consequences escalates. Findings indicate that climate change will augment crop yield variability in numerous places. The potential effects on crops other than primary cereals have been inadequately researched.

The models employed for projecting crop yields typically neglect the influence of climate change on ecosystem dynamics, including the interactions among crops, weeds, and pests, as well as the repercussions for pollinators. Pests and diseases are expected to migrate due to climate change, impacting previously unaffected regions that are consequently less equipped, both biologically and institutionally, to manage and control them, leading to possibly greater adverse effects. These alterations may also offset the direct beneficial impacts of climate change. In high-latitude regions, climatic conditions will become more conducive to crops, as well as to weeds and pests.

Climate change impacts cattle productivity in several direct and indirect manners. The most significant effects are observed in animal productivity and health, as well as in the yields of forages and feed crops. In several sub-Saharan African nations, declines in animal populations ranging from 20 to 60 percent were documented after severe drought occurrences in recent decades. In South Africa, dairy production may decline by 10 to 25 percent due to climate change. Elevated temperatures and diminished precipitation can lead to significant declines in forage production, exemplified by the 60 percent shortfall of green fodder during the summer of 2003 in France. Climate change and variability are affecting forests and their ability to provide the diverse commodities and environmental services upon which about 1.6 billion individuals rely, either wholly or partially, for their livelihoods and resilience. Evidence indicates that in multiple regions, climate change is leading to diminished productivity and

dieback of trees due to drought and thermal stress, heightened wind and water erosion, amplified storm damage, increased frequency of wildfires, pest and disease outbreaks, landslides and avalanches, alterations in the distribution of forest flora and fauna, inundation and flood damage, saltwater intrusion and sea-level rise, as well as damage from coastal storms. This may compromise the role of forests in enhancing the resilience of agricultural systems, including water and temperature regulation at the landscape scale and the provision of habitats for crucial species such as pollinators.

Climate change impacts capture fisheries and the advancement of aquaculture in both marine and freshwater ecosystems. Impacts arise from both gradual atmospheric warming and related physical (surface temperature of seas and inland waters, ocean circulation, waves, and storm systems) and chemical alterations (salinity, oxygen concentration, and acidity) of the aquatic ecosystem. The frequency of coral reef bleaching has risen, endangering the habitats of one in four marine species. Numerous fish species are already migrating poleward, leading to the swift "tropicalisation" of mid- and high-latitude ecosystems. A significant redistribution in worldwide marine fish catch potential is anticipated, featuring a decline of up to 40 percent in tropical areas and a rise of 30 to 70 percent in high-latitude regions. In the Mediterranean, invasive species from lower-latitude regions have been introduced at a rate of one new species every four weeks in recent years. The abundance and species variety of riverine fish are particularly susceptible to perturbations in water flow quantity and timing, especially during dry seasons when water levels are reduced. Human activities aimed at conserving water in reservoirs and irrigation canals may intensify pressures on river flows. Favourable conditions for all production will shift geographically. Enhancing these circumstances will necessitate modifications in the breeding and management of crops, livestock, trees, and aquatic species. To realise potential advantages, such as extended growing seasons in certain cold regions, substantial modifications in agricultural systems and practices would generally be necessary to adapt to new conditions and mitigate potential adverse effects, such as pest proliferation, to achieve actual production growth.

Production impacts result in economic and societal repercussions, influencing food security. The impact extends from climate to the environment, the productive sector, and economic and social dimensions, introducing various additional risks regarding food availability, access, utilisation, and the stability of these factors for both agricultural and non-agricultural households. At the farm or household level, climate change effects may diminish income levels and stability by influencing productivity, production costs, or pricing. Such fluctuations can diminish the long-term productive potential of households by driving sales of productive capital, such as livestock. Exposure to hazards diminishes incentives to invest in production systems, frequently resulting in adverse effects on long-term productivity, profits, and sustainability. Decreases and threats to agricultural revenue have been demonstrated to impact household capacity and inclination to invest in health and education. Recent investigations demonstrate that the effects of diverse weather anomalies on agricultural income are most pronounced for the most impoverished farmers.

At the national level, exposure to climate risks can induce shocks in agricultural production and food availability, leading to market disruptions, effects on supply and storage systems, and escalations in agricultural commodity prices (food and feed), thereby affecting the accessibility and stability of food supplies for the entire population, especially in countries where a substantial portion of the population allocates a significant share of their income to food expenditures. This induces macroeconomic repercussions for nations where agriculture significantly contributes to GDP and/or serves as a vital source of employment. Climatic

concerns may impede agricultural development by deterring investments. Climatic shocks affecting regions critical to global food supplies can induce distant repercussions through: (i) fluctuations in supply chains and surges in food prices, leading to heightened market volatility; and (ii) alterations in bilateral agreements and import/export activities, resulting in disrupted trade patterns. Climate change is expected to intensify food price volatility. Trade is anticipated to significantly influence the adaptation to climate change-induced alterations in agricultural and food production patterns. Recent observations demonstrate that the impact of climate change on food price volatility is significantly affected by local policy, particularly through the implementation of export limits, which exacerbate price variations. Ultimately, global markets will remain inaccessible to the most impoverished nations and populations lacking adequate purchasing power.

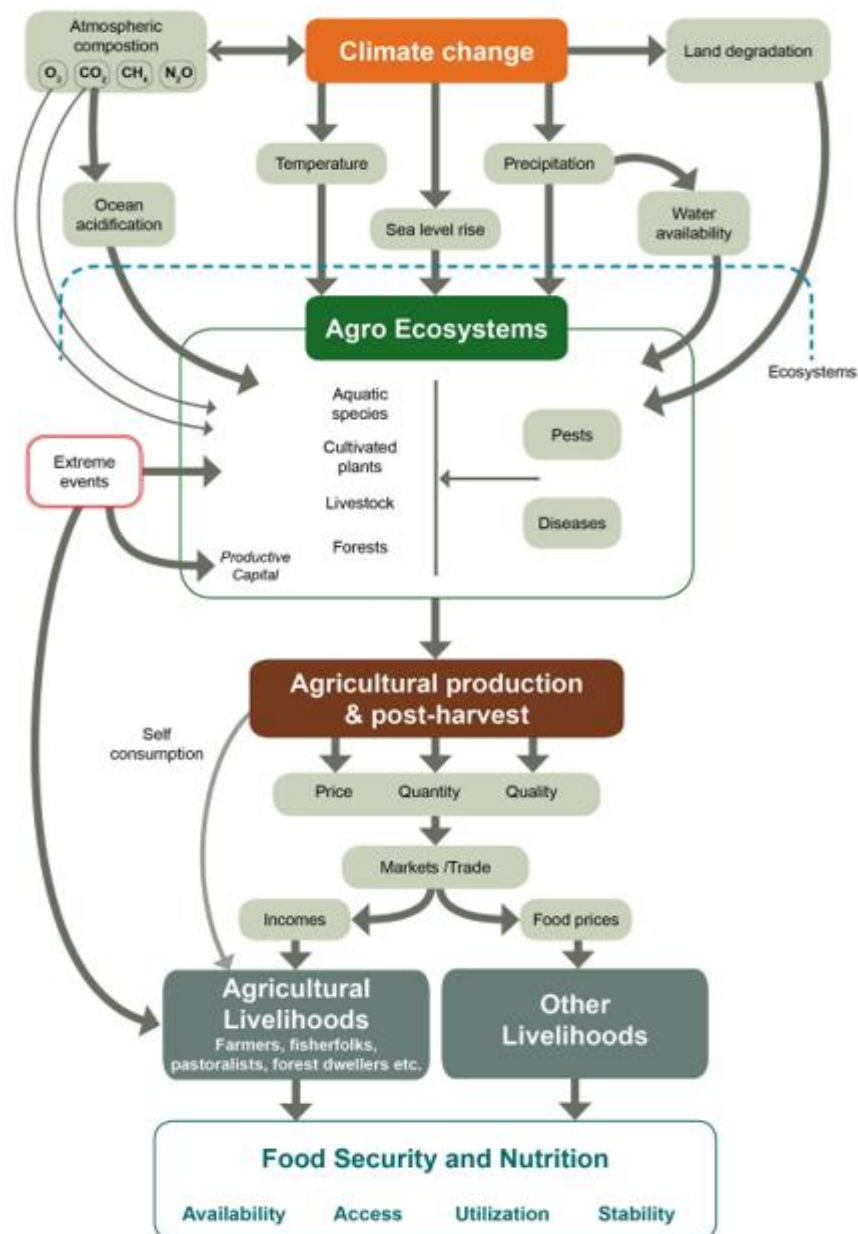


Figure 1. Schematic depiction of the cascading consequences of climate change on food security and nutrition.

Source: <https://openknowledge.fao.org/server/api/core/bitstreams/a4fd8ac5-4582-4a66-91b0-55abf642a400/content>

2.1 Climate change impacts food security across all dimensions: access, availability, utilisation and stability.

Climate change impacts food production and, consequently, food availability (IPCC, 2014). Climate change would affect the livelihoods and income of small-scale food producers and, through increased food prices and volatility, the livelihoods of impoverished net food purchasers, thereby limiting access to food (FAO, IFAD, & WFP, 2015). The effects of climate change on nutrition have been significantly under-researched, though studies indicate potential declines in protein, zinc, and iron content due to elevated CO₂—especially in cereals and cassava (Myers et al., 2014). Climate change can significantly affect the quality of drinking water, which is essential for nutrient absorption (FAO, 2016). Climate change also affects food safety, including the incidence and distribution of foodborne illnesses (IPCC, 2014). Increased variability and more frequent extreme events further undermine the stability of food supply, access, and utilisation (FAO, 2016).

The net impact of climate change on food security depends upon the vulnerabilities of the systems involved (IPCC, 2014). Vulnerabilities amplify impacts at each stage of the climate-induced "cascade of risks" (FAO, 2016). Vulnerability increases when households experience recurrent shocks that erode resilience. The most vulnerable populations are those dependent on agriculture and natural resources, who possess limited adaptive capacity (IPCC, 2014). In highly food-insecure and unequal regions, increased drought frequency disproportionately affects poor households and heightens gender disparity in resource access (HLPE, 2012). Indigenous communities reliant on ecosystems face high risks, particularly in the Arctic, mountains, small islands, and coastal areas (IPCC, 2014). Fishers, aquaculture workers, and post-harvest labourers also face heightened exposure (FAO, 2016). In some cases, migration becomes the only adaptation option (IPCC, 2014).

3. RESPONSES: ACHIEVING FOOD SECURITY AND OPTIMAL NUTRITION IN THE CONTEXT OF CLIMATE CHANGE

3.1 Activate social protection to enhance resilience

Social protection strengthens livelihood resilience and reduces vulnerability to climate risks (FAO, 2016). Social protection—encompassing safety nets and livelihood-enhancing measures—can address key household vulnerabilities and enable access to food without undermining productive assets (FAO, IFAD, & WFP, 2015). Programs targeted toward women are particularly effective (HLPE, 2012). A joint FAO–IFAD–WFP report shows that extreme poverty and hunger can be eliminated by 2030 through combined investments in social protection and rural/agricultural development, costing an estimated USD 267 billion annually (FAO, IFAD, & WFP, 2015). Climate change increases the need for such investments (FAO, 2016).

Disaster risk reduction (DRR) must complement social protection. Evidence shows that for every USD 1 invested in DRR, USD 2–4 is saved through reduced impacts (FAO, 2015). A shift toward proactive risk management is required. Social protection programs are crucial in this endeavour, demonstrating efficacy in disrupting the cyclical nature of poverty and hunger. Social protection encompasses a diverse range of instruments and purposes, including both safety nets and "safety ropes," which are methods that improve income-generating capabilities and possibilities for the impoverished and vulnerable populations. Effective, well-structured social protection would address key vulnerabilities of households to climate hazards. Financial assistance offered to the impoverished and malnourished via social protection can facilitate their access to adequate food to satisfy their fundamental nutritional requirements, without

jeopardising the future productivity of their livelihoods. Such initiatives will be especially effective if directed towards the needs of women.

A recent report by FAO, IFAD, and WFP indicated that it is feasible to eradicate extreme poverty and hunger by 2030 through the integration of public investment in social protection and collaborative public and private initiatives to enhance investment in productive sectors, particularly in rural areas and agriculture, thereby fostering pro-poor and gender-inclusive growth. The total anticipated expenditure is projected to average USD267 billion annually from 2016 to 2030. Climate change renders these investments increasingly imperative. It also undermines the long-term achievement of the goal of eradicating hunger, necessitating the preservation of substantial safety nets and safeguards, together with increased investments to address extra threats.

These activities must be complemented by disaster risk reduction and disaster risk management (DRR/DRM) techniques to mitigate the hazards associated with extreme events. A shift in the strategy for disaster risk reduction is necessary to emphasise the mitigation and proactive management of hazards instead of only responding to incidents. Empirical research indicates that disaster risk reduction (DRR) is economically advantageous: for each USD1 invested in DRR, USD2–4 is recouped through mitigated or diminished catastrophic consequences.

3.2 Enhance the resilience of agricultural systems

Agricultural resilience depends on context-specific adaptation strategies (IPCC, 2014). Efficient water use is essential as climate change alters hydrology (FAO, 2016). Adaptation options include water harvesting, improved irrigation technologies, reduced tillage, and soil carbon enhancement. Crop adaptation strategies include stress-tolerant varieties, crop diversification, adjusted planting dates, and improved post-harvest handling (IPCC, 2014). Such strategies may increase yields by 7–15% under certain conditions (FAO, 2016).

Livestock adaptation may include heat-tolerant breeds, improved feed systems, and climate-resilient housing (FAO, 2016). Many locally adapted breeds remain underutilised due to gaps in breeding programs and market limitations. Healthy, diverse forest ecosystems are more resilient to climate stressors (IPCC, 2014). Strategies include integrated pest management, reduced-impact logging, forest restoration, and sustainable extraction of non-timber forest resources.

Fisheries and aquaculture adaptation include species diversification, flexible access frameworks, selective breeding, and resilient cage/pond systems (FAO, 2016). Climate-induced shifts in species distribution require governance reforms. Diversification across production systems—crops, livestock, forestry, aquaculture—reduces risk (FAO, 2016). Landscape-level adaptation, such as watershed and coastal zone management, erosion control, and pest management, requires strong local institutions (IPCC, 2014). A variety of adaptation strategies exists for livestock production across several scales: individual animals, feeding and housing systems, production systems, and institutional frameworks. They vary between small-scale livestock production characterised by low market integration and large-scale production marked by strong market integration. Specifically, the breeding of livestock, as well as feed crops and forages, constitutes a significant element in enhancing resilience to climate change. Numerous animal breeds are already proficiently adapted to elevated temperatures and severe settings; nevertheless, their broader dissemination is hindered by the insufficient characterisation and enhancement within organised breeding programs and by trade limitations. Traits associated with adaptation are more challenging to investigate and document than

production traits, exhibit lower heritability, possess greater non-additive genetic variation and phenotypic variance, and are more vulnerable to genotype-by-environment interactions.

Robust, diversified forest ecosystems have greater resilience, enabling them to withstand stress, recuperate from damage, and autonomously adjust to changes. Healthy ecosystems have greater resilience to adverse biotic and abiotic factors compared to stressed ecosystems with compromised ecological processes. Optimal practices encompass integrated pest management, disease mitigation, forest fire management, the use of reduced impact logging in production forests, regulation of non-wood forest product collection and livestock grazing within sustainable limits, and enforcement of forest legislation. Restoring degraded forests to their optimal conditions, hence reinstating ecosystem functioning, is a principal technique for enhancing resilience.

Fishing and aquaculture operations and management must adapt to evolving species composition, geographic distribution, and heightened dangers at sea. Alterations in fish distribution will necessitate the adaptation of fishing efforts through flexible allocation and access frameworks. Options for adapting to declining or fluctuating yields in fisheries technologies and management must be meticulously evaluated to prevent worsening the overexploitation of fisheries or adversely affecting habitats. A range of adaptive practices for aquaculture has been discovered, including varied and integrated aquaculture systems, water quality monitoring, species selection, selective breeding, genetic enhancement, site selection, and enhanced cage and pond building.

Enhancing variety within manufacturing systems will mitigate hazards. This can manifest in various ways: integrating multiple production types (crops, forestry, aquaculture, and livestock); augmenting the diversity of species, populations, variations, or breeds; and enhancing the utilisation of genetically diverse resources, such as crop multilines. Adaptation actions may be implemented at the landscape level, including watershed preservation and management, fire management, erosion control, coastal zone management, and pest and disease management. Implementing a landscape management method necessitates consideration of the area's physical and biological characteristics, alongside the organisations and individuals that impact it. Adaptation at the landscape level necessitates suitable structures and policies to enhance the coping capacities of communities.

3.3 Invest in robust agricultural development

Agricultural development is one of the most effective drivers of poverty reduction (World Bank, 2008). Agricultural GDP growth is three times more effective at reducing poverty than growth in other sectors in agrarian economies (World Bank, 2015). The HLPE highlights the central role of smallholder-led development (HLPE, 2013).

Climate adaptation must be integrated into agricultural investment programs to maximize impact (FAO, 2016). Public investment—especially in research, irrigation, land restoration, and extension—catalyses private investment. Improved climate information services (weather data, forecasts, projections) support adaptive decision-making (FAO, 2016). Managing genetic resources is essential for long-term resilience. This includes in-situ and ex-situ conservation, breeding programs, genetic enhancement, and the introduction of new climate-tolerant species or varieties (FAO, 2016).

3.4 Facilitate adaptability via policies and institutions

Strong institutions and policies are required to address climate-related risks such as water scarcity, pests, diseases, and wildfires (IPCC, 2014). Secure land tenure—supported by the

Voluntary Guidelines on the Responsible Governance of Tenure (VGGT)—is crucial for long-term investment (CFS, 2012). Natural resource governance must consider pastoralists, indigenous peoples, and community-based management systems (HFLE, 2013). Smallholder access to finance, insurance, markets, and value chains is essential for climate adaptation (World Bank, 2015). Financial policies should address risks such as price volatility and transaction costs. Climate policies should integrate agriculture and food security. Many countries include agriculture in their National Adaptation Plans (NAPs) and Intended Nationally Determined Contributions (INDCs) (UNFCCC, 2015).

3.5 Augment the role of markets and commerce in ensuring food security stability.

Global markets can stabilise supply and prices (FAO, 2016). To reduce volatility, strategies include removing trade barriers, improving market efficiency, and strengthening agricultural information systems. The Agricultural Market Information System (AMIS) enhances transparency in global markets by tracking production, stocks, trade, and utilisation (AMIS, 2011). Climate effects on future food supply indicate an increased significance of commerce due to altered production patterns and climate disruptions. Attention has centred on three potential ways to mitigate market volatility: restricting trade limitations, expanding and enhancing markets, and optimising information dissemination. The absence of dependable and current data regarding agricultural supply, demand, stockpiles, and export availability has led to recent price volatility in food markets. An Agricultural Market Information System (AMIS) has been established to oversee global markets for wheat, maize, rice, and soybeans (including production, utilisation, stocks, and trade) to identify conditions that may necessitate international policy intervention and, if required, convene principal exporting and importing nations to devise and execute suitable solutions.

3.6 Enhance regional and global collaboration

Climate change will shift production zones across borders, requiring transboundary collaboration (IPCC, 2014). International cooperation is essential for managing fish stocks, conserving genetic resources, and controlling transboundary pests. The International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) and the International Plant Protection Convention (IPPC) provide frameworks for exchange, conservation, and phytosanitary protection (FAO, 2016).

4. IMMEDIATE ACTION ON CLIMATE CHANGE IS ESSENTIAL TO GUARANTEE FOOD SECURITY FOR ALL, BOTH NOW AND IN THE FUTURE

Climate change generates cascading risks affecting ecosystems, productivity, markets, and livelihoods (IPCC, 2014). Vulnerable populations—especially those in climate-sensitive regions—face the earliest and most severe impacts (FAO, 2016). Adaptation strategies must be integrated, gender-responsive, multi-sectoral, and multi-scalar (HLPE, 2012). Long-lead adaptation actions such as breeding, forest restoration, and infrastructure should begin immediately. The National Adaptation Plan (NAP) framework under the UNFCCC provides a pathway (UNFCCC, 2015).

Enhancing food security resilience against climate change necessitates several actions, including social protection, agricultural techniques, and risk management. Adaptation to climate change in agriculture and food systems for food security and nutrition necessitates enabling investments, policies, and institutions across multiple domains. For optimal effectiveness, such treatments must be incorporated into integrated strategies and plans. These initiatives must be gender-sensitive, multi-scalar, multi-sectoral, and involve several stakeholders. They must be articulated transparently, taking into account the various

characteristics (social, economic, environmental) of the concerns and the diverse timeframes required for implementation and support of the reforms. They have to be founded on evaluations of dangers and vulnerabilities, incorporate lessons from experience and advancements, and be consistently monitored, evaluated, and revised. Middle- and high-income nations are progressively conducting frequent evaluations; nonetheless, countries without this capability will require targeted assistance. The National Adaptation Plan process established under the UNFCCC offers the possibility to incorporate food security and nutrition as a primary priority. National policies and goals must also be bolstered by improved regional and international collaboration.

Immediate actions by many stakeholders are essential to facilitate responses in the short, medium, and long term. Certain medium- and long-term responses necessitate prompt enabling actions and planning, alongside the immediate execution of investments, particularly those that demand extended timeframes for development and deployment in the field: forestry, livestock breeding, seed multiplication, research and development, innovation, and knowledge transfer to facilitate adaptation.

For the impoverished globally, adjusting to climate change and securing food supply are interconnected imperatives. A paradigm change towards agriculture and food systems that are increasingly robust, productive, and sustainable is necessary. Consequently, the global community must take immediate action to eradicate hunger and malnutrition, facilitate the agricultural sector's adaptation to climate change, and mitigate climate change to maintain conditions that secure and protect universal food security and nutrition. Agriculture plays a crucial role in this endeavour, with food security as the foremost objective.

5. CONCLUSION

Climate change poses an immediate and substantial threat to global food security (IPCC, 2014; FAO, 2016). Its impacts undermine agricultural systems, ecosystems, markets, and livelihoods. Vulnerable populations—particularly smallholders, pastoralists, fishers, and indigenous groups—face disproportionate harm. Ensuring food security requires integrated, multi-sectoral strategies that build resilience through social protection, climate-smart agriculture, improved governance, investment in innovation, and international cooperation (FAO, 2016; HLPE, 2013). Climate-related delays will magnify long-term risks. A global shift toward resilient, productive, and sustainable agriculture is therefore imperative. Climate change has emerged as one of the most significant and immediate threats to global food security, exerting profound impacts on agricultural systems, natural resources, markets, livelihoods, and nutrition. The evidence presented in this paper demonstrates that climate-induced hazards—ranging from rising temperatures and erratic precipitation to shifting pest pressures, degraded ecosystems, and extreme weather events—are already diminishing crop yields, reducing livestock productivity, destabilising fisheries, and eroding the ecological foundations upon which food systems depend. These effects are neither uniform nor equitable; they fall most heavily on the poor, particularly smallholder farmers, pastoralists, fishers, and forest-dependent communities in vulnerable regions. Without decisive action, climate change will further undermine progress made in reducing hunger and malnutrition, threatening global stability and sustainable development.

Ensuring food security in a changing climate requires more than improving production; it demands integrated, multi-scalar, and multi-sectoral strategies that simultaneously enhance resilience, reduce vulnerabilities, and support inclusive development. Strengthening social protection systems, expanding climate-smart agricultural practices, improving water and land

governance, conserving genetic resources, and investing in smallholder-centered agricultural development are central pillars for reducing risk and building adaptive capacity. These actions must be reinforced by enabling policies, equitable institutions, gender-responsive approaches, and strong market and financial systems that support producers and consumers alike. International cooperation remains indispensable, particularly for managing transboundary risks, facilitating genetic resource exchange, stabilising trade systems, and strengthening early warning and knowledge-sharing platforms.

Above all, the urgency of immediate action cannot be overstated. Many adaptation strategies—such as crop breeding, forest restoration, and infrastructure development—require long lead times before benefits are realised. Delayed responses will heighten both human and economic costs, deepen inequalities, and compromise the ability of future generations to meet their food and nutrition needs. A global paradigm shift toward resilient, productive, and sustainable agriculture is therefore essential. Confronting climate change while ensuring food security is not merely an environmental challenge—it is a humanitarian, economic, and moral imperative. The global community must act swiftly and collaboratively to build food systems capable of withstanding climatic shocks and securing a healthy, nourished future for all.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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DESIGN, INSTALLATION PROCEDURES, AND OPERATIONAL CONSIDERATIONS FOR DOMESTIC SOLAR PHOTOVOLTAIC SYSTEMS: COMPONENTS, WIRING, SAFETY AND PERFORMANCE REQUIREMENTS

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ABSTRACT

Solar photovoltaic (PV) systems have become increasingly important as global demand for clean, reliable and affordable electricity rises. This growth is driven by concerns over fossil-fuel depletion, environmental degradation, geopolitical conflicts, and fluctuations in global energy prices. Solar energy offers a renewable, emission-free alternative that reduces greenhouse gas emissions and mitigates climate change. This paper provides a comprehensive overview of the principles, components, installation processes, and safety practices required in domestic solar PV systems. It examines key system elements including solar panels, batteries, inverters, wiring, mounting structures, and appliances, while explaining the technical principles behind series and parallel connections, battery management, grounding, and grid-tie operations. The study further outlines step-by-step installation procedures, electrical integration, inspection requirements, and maintenance needs to ensure system longevity and efficiency. A structured literature review highlights international best practices in panel orientation, battery technologies, inverter functions, and safety systems. Findings show that proper installation planning, component selection, and adherence to safety protocols significantly enhance performance, operational reliability, and user safety. The paper concludes that solar PV systems play a vital role in promoting energy independence, environmental sustainability, and long-term energy security for households and communities.

1. INTRODUCTION

In this article, we will explain how to install solar panels and detail their advantages. Due to rising energy costs, foreign conflict and damage to nature, solar energy has become a more popular way to generate energy. The largest benefit of solar energy is that it doesn't add any greenhouse gas emissions to the environment. Rather than adding to global warming like fossil fuels, solar energy is a clean and green source of power. Solar panels allow us to produce energy in a way that greatly decreases our impact on the environment and helps address the problems of climate change.

Solar energy can help us use less of our standard energy sources. Alternative energy sources such as coal and oil are limited in what is available and may soon cost more. Because it is renewable, solar energy can always be accessed and does not have the same large changes. This action could reduce our energy prices and give us a reliable way to meet our needs well into the future.

In addition, solar energy contributes to less political tension than are seen with traditional forms of energy. Since many fossil fuels are found in unstable nations, this often results in disputes over power sources and disputes over energy. Switching to solar helps us tackle these challenges and achieve secure energy supplies.

Anyone with the right knowledge, training and skills can find solar design and installation fairly easy. We will now cover the components needed for solar installation and what they do. A solar panel includes other components that are needed for its proper operation. These include

- a. Solar System
- b. Solar Panels
- c. Mounting System
- d. Battery
- e. Inverter
- f. Connecting Wires
- g. Appliances

The solar system is made up of the Sun and everything that orbits around it, including satellites. However, in this paper, we will only refer to the Sun and Earth as the solar system. Solar energy is the energy that originates from the Sun, reaching us in the form of light and heat. Nigeria has a land area of 923,786 square kilometres and receives approximately 1500×10^9 Mega Watthour (MWh) of solar radiation annually. The average daily impact is around 19 Mega Joules (MJ) per square meter per day. The duration of this radiation is typically around 6 hours per day, although it varies from about 4 hours in coastal areas and up to approximately 9 hours in the far North (<https://eyowhite.com/solar-energy-in-nigeria-untapped-potential-and-recent-progress/>).

A solid cell or photovoltaic cell is a device that converts light energy into electrical energy through the photovoltaic effect. This effect generates voltage across the P-N junction in a semiconductor through the absorption of light radiation. Devices that use this effect are called photovoltaic devices. Solar panels convert solar energy into electrical energy for the purpose of charging batteries. To effectively use solar panels, they are connected in series, known as a string, and in parallel connections, known as an array, to collect a good amount of sunlight. This collected sunlight is capable of supplying the amount of electricity needed to run an entire household.

Solar panels are rated in different watts, depending on their use. In Nigeria, In Nigeria, the most common types of solar panels are polycrystalline and monocrystalline, with polycrystalline often preferred for its affordability and suitability for large installations, while monocrystalline is favored for its higher efficiency in smaller spaces. Sizes vary widely depending on energy needs, but common residential wattages range from **100W to 550W**. To install a 5-kilowatt solar system in a house, 10 plates of 545 watts would be required. Two types of connections are done while connecting the solar panels.

In a series connection, each plate is connected to its neighbouring plate, meaning that the positive terminal of one plate is connected to the negative terminal of the adjacent plate. This arrangement forms a string, allowing the voltage of each panel to add up to the total number of plates. [3] However, the current remains the same as that of an individual plate. This type of configuration is used when high voltage is required in the system. Side-by-side connections of plates link the positive terminals of each plate and the two negative terminals together. This means that the total voltage doesn't vary, but the total current has the sum of the separate plate currents. This method is important for providing high operating current.

Making these types of connections means ensuring that the solar panel's input voltage is lower than the inverter's PV voltage maximum. To make sure the voltage and current are evenly balanced, we assembled two arrays of five solar panels, joined them in parallel and attached them to the system.

A solar panel stand is made to support solar panels as shown in Figure 1. Their structure is often aluminum which enables them to resist problems caused by the weather. Solar stands keep the panels lifted so they can be angled right for maximum benefit. Solar panel wiring in series is shown in Figure 2.



Figure 1: Mounting the solar panels (ground and Roof-mounted

Source: <https://solarssk.com/solar-ground-mounting-systems/>; <https://greentumble.com/types-of-solar-panel-mounting-systems-and-their-installation>).

Solar panels wired in series

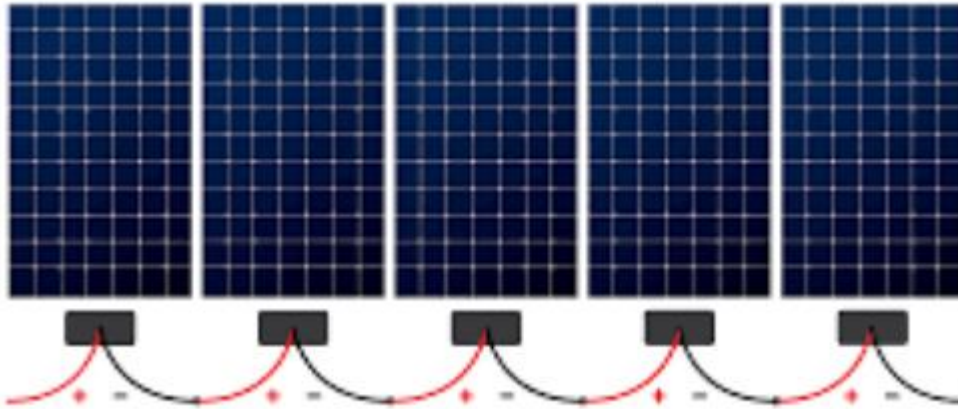


Figure 2. Solar panel wiring in series. (Source: <https://www.solarreviews.com/blog/do-you-wire-solar-panels-series-or-parallel>)

Solar panels wired in parallel

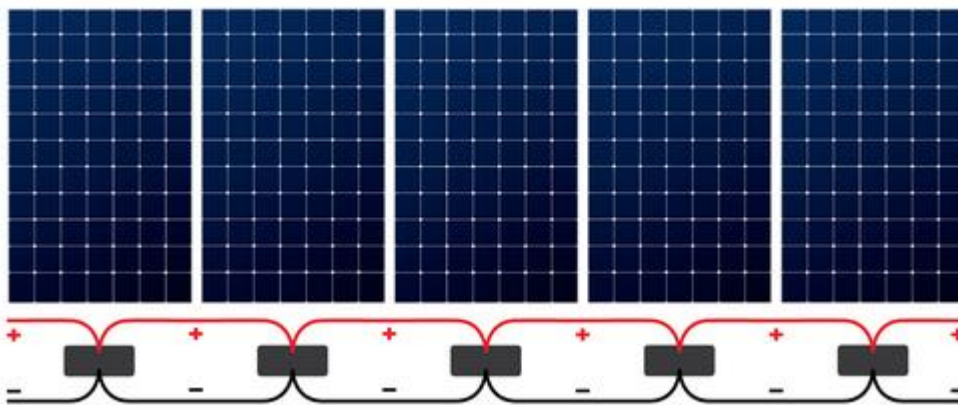


Figure 3. Solar panel wiring in parallel.(Source: <https://www.solarreviews.com/blog/do-you-wire-solar-panels-series-or-parallel>)

2. LITERATURE SURVEY

Solar photovoltaic (PV) technologies have rapidly expanded due to increasing energy demand, environmental concerns, and the need for decentralized power solutions. Studies show that solar energy reduces greenhouse gas emissions, improves energy security, and supports global climate change mitigation (IEA, 2020). The cost of PV modules has declined significantly over the past decade due to technological advancements and increased manufacturing scale (REN21, 2023). These trends have made solar installations more accessible for households, rural communities, and industries.

Proper installation remains essential for ensuring the performance and durability of PV systems. According to Kalogirou (2014), installation quality directly affects energy yield, system lifespan, and user safety. Therefore, understanding system components—panels, batteries, inverters, wiring, and mounting structures—is necessary to guarantee optimal function and compliance with electrical standards.

Solar electricity generation largely depends on the angle and direction of solar panels. Research shows that tilt angles between 20° and 35° provide optimal yearly energy production in regions

with high solar irradiance (Muhsen et al., 2017). Similar findings apply to Pakistan and other tropical regions, where 20°–30° tilt is considered ideal (Shukla et al., 2016).

Mounting systems—including rack, roof, and ground mounts—anchor panels securely while ensuring proper ventilation and alignment (Razak et al., 2016). Aluminum and galvanized steel are commonly used due to their durability and resistance to corrosion. Proper mounting prevents wind uplift, water penetration and structural failure, especially on rooftops (Kalogirou, 2014).

PV cells operate based on the photovoltaic effect, producing direct current (DC) electricity when exposed to sunlight (Sharma & Kumar, 2020). To increase voltage or current, solar panels are wired in series or parallel configurations. Series connections increase voltage while maintaining current, whereas parallel connections increase current while keeping voltage constant (Walker & Brown, 2019). The literature emphasizes the importance of maintaining voltage levels below the inverter's maximum input rating to avoid damage.

Combiner boxes, junction boxes, and appropriate cabling are critical for merging solar outputs safely (Ramabhotla & Natarajan, 2018). International standards such as the National Electric Code (NEC) mandate proper conductor sizing, insulation, surge protection, and grounding to ensure safe operation (NEC, 2020).

Battery storage is essential in off-grid and hybrid solar systems. Two broad categories dominate literature: lead-acid and lithium-ion batteries. Lead-acid batteries—including flooded and sealed types—are economical but require ventilation and regular maintenance (Bahramipanah et al., 2018). Deep-cycle batteries can discharge up to 80% of their capacity without damage, making them suitable for PV applications.

Lithium-ion batteries offer higher efficiency, longer lifespan, deeper discharge, and better energy density, though at higher cost (Mao et al., 2018). Temperature variations significantly impact battery health, and studies recommend maintaining storage temperatures around 25°C to prolong battery life (Riffat & Cuce, 2018). Proper wiring, ventilation, and safety precautions reduce risks such as thermal runaway, gas emissions, and electrical fires.

Inverters convert DC power from solar panels into alternating current (AC) suitable for homes and the grid. Modern inverters integrate monitoring systems, safety features, and automatic shutdown in hazardous conditions (Zhang et al., 2019). Three main inverter types dominate installations:

- *String inverters*: cost-effective and widely used
- *Micro-inverters*: improve performance where shading occurs
- *Hybrid inverters*: used in storage-based systems

Grid-tied inverters synchronize with grid electricity to ensure safe operation and enable net metering (IEA PVPS, 2021). Overvoltage, ground-fault and arc-fault protection mechanisms reduce hazards and system failures.

Solar installations involve electrical work, heavy lifting, and roof activities; hence safety is a core requirement. International standards emphasize the use of gloves, insulated tools, harnesses, grounding conductors, and fall protection systems during installation (NEC, 2020; OSHA, 2019). Research on PV system failures confirms that improper grounding, loose connections, and poor wiring are leading causes of fires and electrical accidents (Brooks & Dunlop, 2018). Planning requirements include system design evaluation, load assessment,

shading analysis, wiring diagrams, and component compatibility checks (Razak et al., 2016). Safety assessments ensure electric shock prevention, surge protection, battery gas ventilation and structural integrity of mounting frames.

Maintenance improves long-term performance. Dust, debris, and shading can reduce output by up to 25% if not regularly addressed (Kazem et al., 2016). Studies recommend cleaning panels several times per year depending on climate conditions. Inverters and electrical components require periodic inspections to ensure no loose connections, corrosion or overheating (Kalogirou, 2014).

Monitoring systems track production levels, voltage, current, and faults in real-time, allowing early intervention and improving system reliability (Zhang et al., 2019). Vegetation trimming and professional maintenance also extend system lifespan.

Daylight creates power with solar panels which is then stored in batteries ready for use. The stored energy is sent to the panel to keep up the output when it doesn't produce enough power. Any solar system relies most on its batteries, but they are the easiest to damage. For this reason, the battery should have enough Ampere-hour (Ah) capacity to meet the system's power requirements which are usually greater when the skies are overcast.

There are two types of batteries: deep cycle discharge (used in photovoltaic (PV) systems) and shallow cycle discharge (used in cars). The daily discharge rate of shallow-cycle batteries should not exceed 10% to 20% of their Ah capacity. Discharging them beyond this point without recharging them may shorten their lifespan. In contrast, deep-cycle batteries can discharge between 60% and 80% of their Ah capacity. It's important to remember that a battery with a 1-amp discharge rate will have a larger Ah capacity than one with a 4-amp discharge rate. For instance, a 100 Ah capacity battery can provide 1 amp of power for 100 hours. To generate enough electricity to power the entire residence, two 24-volt 200 Ah batteries wired in series are used in the 5KWatt system.

An inverter is a key component of a solar electric system because it transforms the direct current (DC) electricity produced by solar panels into alternating current, or AC, electricity, which may be utilized to power lights, appliances, and other electrical equipment in residences or commercial buildings. The function of an inverter in the solar power setup is broken down as follows:

DC to AC Conversion: The solar panels in your home generate direct current (DC). Most homes and the grid itself depend on alternating current (AC). An inverter is used to change the DC electricity made by solar panels into AC, so it can be used by the household appliances and sent to the electrical grid.

Voltage Regulation: They also modify the voltage so that the power generated by solar is suitable for both the grid and the devices working in your home. As a result, equipment in the electrical system continues to operate safely and no unnecessary damage happens. Grid-tied solar panels regularly use inverters to match the electricity generated from the cells with that on the electrical grid. With this synchronization, the solar system operation is secure and it can put extra power back onto the grid. (Kalogirou, 2023) *Monitoring and Control:* There are many inverters today that give people access to real-time monitoring of their photovoltaic system. It means following the solar panel system's total energy output, the energy being consumed and the way the system works. Some inverters also come with online systems or

apps so you can control and watch your solar system from anywhere.

Safety Measures: A range of safety features is built into inverters to protect solar power systems and avoid electrical issues. Proper operations and safety of the system can be protected with ground fault, overvoltage and overcurrent protections. For power to pass safely between all the parts of a solar system, connecting cables are very important. Here, I explain the different kinds of wires and what role they play in a standard solar installation.

Solar Panel Wiring: To obtain suitable voltage and current, solar panels are often arranged either in series or parallel. Copper wires cover each solar panel and are often coated to make them safe against shock. Solar panel electricity is carried by the cables to be put together at the junction or combiner box.

Combiner Box Wiring: In big solar systems, combiner boxes gather each panel's wiring, then send it to the inverter. The correct electrical cords connect each solar panel string to the contacts in the combiner box. Following this, the mixtures of DC from the combiner box go to the inverter (Kabir et al., 2018).

Inverter Wiring: DC input terminals are used to link the inverter to the solar panels. Using the proper connections, wires transporting the DC current from the photovoltaic cells are linked to these terminals. The building's electrical panel receives the alternating current (AC) that the inverter has transformed from direct current (DC).

Electrical Panel Wiring: The building's electrical panel, sometimes referred to as the distribution board or breaker box, receives the AC energy generated by the inverter. Usually, insulation and electrical wires with the proper gauge are used for this. The circuit breakers or fuses in the panel, that distribute power to different circuits throughout the building, are connected to the wires.

Grid-Tied System Wiring for Grid Connections: Adding solar systems to the utility grid requires wires in grid-tied configurations. Once on the grid, the solar-powered AC electricity takes over powering the building when it is synchronized with the grid.

Grounding Wiring: The safety of a solar power system is achieved mainly through correct grounding. To prevent electric shock or fire due to any stray electricity, grounding wires are hooked into the solar panels, inverter systems and a variety of metal parts.

Your safety and the efficiency of the solar system will be best served if you adhere to both manufacturer and local electrical rules when wiring everything together. Moreover, the safety of the solar system over the long term and the reduced chance of electrical risks are both possible with the use of top-quality parts and suitable installation approaches (Hernández-Callejo et al., 2019)

In a solar system installation, the kind of appliances chosen can make a big difference in how much energy is used and how efficient the system is. Before installing appliances, keep the following suggestions in your mind:

Energy Efficiency: Use equipment that uses the smallest amount of electricity. Buy only appliances that have been certified for energy efficiency by ENERGY STAR. Solar-powered appliances help you get the most out of your system and decrease your energy bill.

Grid-Tied and Off-Grid Systems: Off-grid systems differ from grid-tied systems, so your solar choices will affect the appliances you buy. Because these homes are off the grid, solar power runs them and the appliances used in such homes are usually made to be power efficient and suit off-the-grid living. You can connect regular home appliances to grid-tied panels, but it is smart to pick energy-saving ones to use less electricity.

Size of Appliances: Be certain that the appliances you intend to use are sized according to your solar energy system. To find out how much power an appliance uses, count its wattage or kilowattage and the length of time it is running. You can simplify your analysis by looking at how much your solar system and battery storage can supply shown in Figure 4.

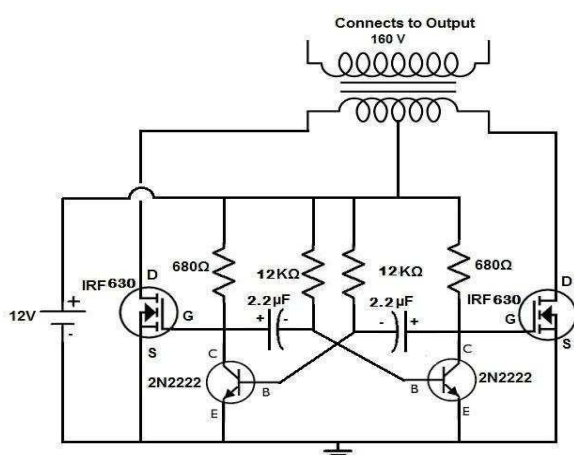


Figure 4. Schematic of appliances connection.

Load Control: One way to make better use of your solar system's power is to install and use load control methods. A lower total demand for power might be achieved by carrying out energy-intensive activities at the brightest hours or by turning on lower energy-use appliances. **Battery Compatibility (Off-Grid Systems):** Choose appliances matched to your battery voltage and charger if you are not linked to the main grid. It is possible that a few pieces of equipment may work better with conventional electrical sources than they do with battery-powered solar and these can be altered or added for better operation.

Backup Power Requirements: Get appliances that work with backup power, so you can keep using them if the electricity is often not available. Even when the grid fails or sunshine is limited such systems will ensure critical services continue.

Appliances That Work with Solar Power: A limited number of appliances are specially built to be powered by solar electricity systems. Examples of solar energy devices are solar-powered lights, solar freezers and solar water heaters. Getting these tools can make your solar installation run more smoothly and help the environment. Make sure the choices in monitoring and control on your appliances match your solar panel setup. As a result, you can check your energy use, improve your efficiency and turn on or off equipment from another location to save energy (Bird et al., 2016)

3. STEP-BY-STEP INSTALLATION OF SOLAR PANEL

There is a sequence to installing a solar system, starting with designing, planning and then mounting the panels and joining the system to your home's electrical grid. This section will walk you through the whole process:

In the planning stage, your energy needs are studied closely and solar panels are evaluated for suitable installation on your property. Remember to think about the area you have, the shade in your yard and where the roof is facing. Define the system's size, what kind it is (options include ground-mounted and rooftop) and how it will be connected to the electric grid (off-grid or grid-tied). Get the necessary consent from utility firms, organizations for homeowners or city agencies before starting. A properly designed solar system yields more energy, complies with rules and fits what you require.

Select your solar panels by considering how efficient they are, their expected lifespan, the kind of guarantee they offer and how they look. Make sure to check how efficient the units are, what the manufacturer is known for and if the solar panels are monocrystalline or polycrystalline. Work out the number of panels needed to accomplish your energy goals. Talk to solar professionals or engineers to help you pick the best solar panels for yourself and your budget. Make sure the solar system you get is compatible with your chosen system mounting method and the inverter you want.

a. Inverter Installation

Depending on your panel design and energy needs, choose the right inverter type (string inverter, micro-inverter, etc.) and capacity. Place the inverter next to the electrical panel in a well-ventilated location. By utilizing DC wire and according to electrical rules and manufacturer requirements, plug the inverter into the solar panels. To transform DC power from the panels into useful alternating current power for your house or the grid, efficient inverter installation is essential.

b. Mounting the Panels

Getting the most sunlight means placing and positioning your solar panels smartly. Properly mounting the equipment will ensure your roof or ground system stays intact against weather elements. Install the solar panels so they are guided by the designer's plans for the angle and spacing. For a solar energy system to work well and last over time, panels must be installed correctly.

To make sure energy does not get lost and harm doesn't occur, route DC wire from the solar panel array to the inverter securely. Connect the inverter to the electrical panel by using conduit that meets the strictures of local electrical rules. Before attaching the inverter outlet to your home's electrical system, always take all the needed precautions and ground it.

c. Electrical Connections and Wiring

Solar panels should be connected to the inverter by using DC wire. In addition, attach and arrange the cables so that they do not lose energy or put you at risk. Be sure to install the conduit according to local electricity rules when you connect the inverter to the electrical panel. It is important to ensure you have grounding and have taken the right steps before you link the inverter outlet to your house's electrical system. For safe and building code-approved wiring, knowing electrical workings is often necessary.

d. Grid Connectivity

Work with your utility company to meet their rules and procedures for setting up solar energy systems on your grid. A bi-directional meter is needed to see how electricity moves from the solar panels to the grid. Team up with the utility company to get all the permission needed and make sure you adhere to interconnection requirements. Being linked to the grid lets you earn credits from net metering, as your extra solar energy goes to the grid (Al Garni, et al., 2016).

e. Examining and Verifying

Check and follow the rules by carefully testing your solar energy system after installation. Check each part such as panels, inverters and electrical links, to see how it works. Work with the suppliers and local authorities to check that codes, rules and connection demands are met during the inspection.

f. Maintenance and Regulation of Solar System

For photovoltaic or PV, panels to operate reliably and efficiently over the long term, maintenance is essential. The following is a thorough overview of solar PV system maintenance procedures:

g. Regular Cleaning

In time, the panels can become covered by dirt, bird and other waste, lowering their effectiveness as they block sunlight. Based on guaranteeing full sunlight usage, cleaning the panel regularly is necessary to keep your solar energy bottom line at its peak. Brush the panels clean by hand using a little bit of water, sparkling water and a water-based detergent solution. The number of cleanings will depend on what surrounds your panels and the weather, but experts suggest washing them several times each year. You should plan regular cleanup after there is a lot of rain or strong winds stirring up dust. Cleaning your solar PV system on a regular basis will ensure its reliable efficiency and avoid energy loss (Abdmouleh et al., 2015)

h. Inspection of Panels

You should inspect your solar panels from time to time to catch and fix any worries before they shorten the system's lifetime or its performance. During your check, watch for chips, cracks and any color changes that might suggest something is wrong. Look at parts of the roof that are next to large neighboring objects, plants or obstacles to see if any shade is preventing the panels from working their best. To ensure everything is secure, the frame and its mount are part of every inspection. Rapidly handling problems found is necessary to prevent added damage and keep the installation running well. Key checkups can keep your solar energy system in top shape for a long time by helping you address Issues early.

i. System Performance Monitoring

If you track your solar PV system's operation, you can follow its energy production, identify trends and notice if anything is working differently than it should. Place devices that measure energy output, monitor how available the system is and check for factors that can reduce the system's performance, for example, soiling or shading. Updates and watches performance reports day by day, to watch for any problems and learn about the health of the system. As action is needed fast in some cases, monitoring systems can also warn when they see abnormal situations. Supervising how your system functions can improve its outputs, show areas where it may struggle and ensure it keeps running efficiently for many years.

j. Testing Electrical and Inverter Components

The solar panels make DC power and the inverters and electrical equipment are needed to convert this into AC electricity for your house or the grid. Proper performance and working can only be ensured for inverters, wiring and electrical connections through routine testing. Regularly inspecting your sound system will help you spot loose parts, signs of rust and overheating. If you want your test equipment to perform well, reference both the user guidelines and industry standards when checking inverters and assemblies. Adapt the inverters when needed for maximum results and safety compliance. Testing inverters and electrical pieces

often allows you to identify faults early and solve them before they become serious (Denholm et al., 2015)

k. Trimming Vegetation

Solar panels work less effectively when shade is cast on them by trees, bushes and shrubs. The plants near the solar panels should be carefully cut back on a regular schedule to avoid them blocking too much sun. Cut back branches that block the light from your solar panels in the hours when they get the most sunlight. Ensure that nothing is next to the panels so they get all the sunshine they can. If you want to get more sunlight on your solar panels, consider planting plants that won't grow tall enough to block the light. Keeping vegetation from your solar panels will allow your system to generate a regular amount of energy and ensure your initial cash outlay is well spent.

l. Professional Maintenance

Though homeowners may manage a lot of the upkeep themselves, it's important to arrange frequent checks by certified techs or experts to keep a solar PV system operating well. Because of their training and the unique equipment, they have, experts can inspect large structures clearly, detect possible problems and perform the necessary corrections or additions. Maintenance crews may check every part of the system, examine the electrical connections and test how everything is working during a visit. They are often able to provide useful advice for improving the system's performance and handling any problems. Reduce costly maintenance by having documents to keep track of all your maintenance work and following the instructions given to you by the manufacturer. If you use skilled maintenance, you can expect a lasting system, less downtime and guaranteed reliability in your solar energy system.

4. SOLAR PANEL INSTALLATION PLANNING & SAFETY

The key to any successful solar panel installation project is having a clearly constructed plan with measures in place to ensure the safety of everyone involved.

In fact, there are a few things an Installer can do before an Installer even unpack the system to make sure the solar installation process goes smoothly from beginning to end. These include:

- Purchasing materials that are not included in the shipment (wiring, tools, etc.)
- Staying organized while unboxing the system
- Inspecting the shipment to ensure nothing is missing or damaged
- Reviewing safety guidelines for installing the system

4.1 Materials needed

Wiring

The electrical wiring diagram will outline the size and length of wire needed for the project. Ask for a copy of the wiring diagram to source materials from the local hardware store.

Junction Boxes & Splices

- Use insulated lugs or other approved splicing devices (no wire nuts for DC splices).
- All junction and splice boxes must meet the voltage and amperage requirements for the circuit they are part of.
- Outdoor boxes must be rated for outdoor use.
- Ground splices typically require an irreversible splice.

AC Breakers & Sub-Panels

- AC breakers are required to import/export AC power from the equipment.
- Circuit breakers have several different mounting options. Check the AC breaker panel for a list of compatible options.
- Dedicated sub-panels are often used to combine AC solar circuits. Sub-panels do not allow for load breakers to be placed inside of them.
- AC sub-panels must be sized with enough headroom to cover the output coming in from the solar circuits.

AC Disconnects & Fuses

- Most systems require a lockable safety disconnect.
- A conventional connection that backfeeds the grid will require a non-fused manual AC Disconnect. This may be included with the system—check the parts list on the quote/order form.
- A line-side tap connection will require a fused manual AC disconnect. The fusing provides the necessary overcurrent protection for the circuit.
- AC disconnects must be mounted outside, generally within 10 feet or in direct line of sight of the main billing meter. Check with the AHJ (Authority Having Jurisdiction) for specific details on placement requirements.

PV Meters

- If a grid-tied system is being installed, the utility may require a dedicated PV meter to measure production coming from the solar array.
- In many cases, an Installer just need to install the meter socket or base. The utility company will install the meter face once an Installer are approved to activate the system.
- Contact the utility company for a list of approved meter sockets

Conduits & Meters

- The NEC (National Electric Code) requires solar wiring to be transitioned to conduit before leaving the array. EMT (electrical metallic tubing) is required unless otherwise specified.
- You can use larger conduit than specified if necessary, to ease the conductors in. **Never** use smaller conduit than what is spec'd in the plans.

EMT vs. ENT Conduit

EMT is a thin-walled, rigid raceway that must be grounded. It is almost always made out of steel. EMT must be used unless the local authority approves ENT conduit for the project.

ENT is a non-metallic, pliable raceway that does not need to be grounded and can be bent by hand. ENT is more cost-effective and easier to work with, but is not allowed under most building codes.

Mounting Materials

Ground Mounting — Ground mounts require concrete, form bracing and 2- or 3-inch mechanical tubing. Since these materials are costly to ship, it's cheaper to source them locally. the racking report will specify the total linear feet of pipe and cubic yards of concrete required for the project.

The Installer will also need lumber to build a frame to hold the pipes in place while the concrete cures. The ground mount section of this solar panel installation guide also contains more information on building a substructure.

Roof Mounting — Buy several tubes of roof sealant to prevent leaks and wind damage. Make sure an Installer get a sealant that is appropriate for use with the roof material. Also, consider buying a good drill if an Installer don't own one. an Installer will be using a long 1/8 inch drill bit and a 7/16 inch deep socket for lag bolts.

Unboxing

After the system arrives, there is a 24-hour window from delivery to submit shipping claims to Unbound Solar. Unpack the system immediately when it arrives to check for damage or missing parts.

- Find a clean, open space where an Installer can unbox and inspect the equipment.
- Place loose parts into resealable plastic bags and label them so they don't get lost.
- Check the contents of the shipment against the packing list to verify everything is there.
- If there are any missing or damaged items, take photos for reference and contact Unbound Solar immediately to fix the issue.
- If an Installer don't plan to install right away, place batteries on a charger ASAP. Batteries can fail if they sit for an extended period of time without charging.
- If an Installer bought micro-inverters or power optimizers, keep any documentation with stickers or QR codes. These will be used to create an array map later on so an Installer know which unit controls which panel.
- *Staying organized while unboxing can make installation easier.*

4.2 Safety Considerations

Since solar installation involves heavy lifting, electrical work, and potentially climbing on the roof, ***safety should be prioritized at all times***. After all, what good is a shiny new solar system if the installer is not around to enjoy its benefits?

Use our solar panel installation guide for ensuring the safety of yourself and others throughout the installation process.

Protective Equipment

Solar equipment can cause cuts, scrapes, lacerations, gouges, and puncture wounds. Use the proper equipment and remember to take breaks to avoid getting fatigued.

- Wear eye protection, gloves, and closed-toe boots at all times.
- Remove all metallic jewelry, including watches.
- Wear long sleeves when mixing concrete to avoid burning the skin. Use a roof anchor and safety harness for roof work.

Fall Protection (Roof Mounts)

If an Installer are installing a roof-mount system, fall protection is required any time an Installer or the helpers are on the roof.

- Install roof anchors.
- Use a safety harness attached to the anchor any time an Installer are on the roof.
- Roof-ready boots with flat soles can help get a grip on roof shingles, tiles, or metal.
- Consider renting scaffolding and/or a boom-lift to make it easier for people and equipment to get to high places.
- Be aware of weather conditions which may make rooftop work temporarily unsafe.

Dig Safety (Ground Mounts)

Even if the feet are firmly planted on the ground, there can still be danger afoot. If you're ground mounting the panels, be sure to always observe the following safety precautions.

- Call the local authority before starting any digging projects to avoid hitting buried gas or electrical lines.
- If an Installer use a concrete truck, don't drive over septic or drainage lines, and avoid low-hanging power or phone lines.
- Avoid contact with wet concrete, which can cause caustic burns on bare skin. Wear gloves, eye protection, and long sleeves.
- Use an N-95 respirator mask if an Installer are mixing the own concrete to avoid inhaling harmful chemicals.
- If an Installer use heavy equipment, get training on how to operate the equipment, or have an experienced operator on site.

The Installer should wear an N-95 respirator mask to avoid breathing unsafe chemicals when mixing concrete.

Electrical Safety

- Remove all metallic jewelry, including watches.
- Keep a multimeter on hand. Check conductors and terminators to confirm there are zero volts present before proceeding.
- Ensure that all wires are stripped and/or terminated properly using a torque wrench/driver when necessary.
- Route wires away from sharp edges and pinch points that could damage the wire.
- *Keep a multimeter handy to ensure no voltage is present before an Installer work on the system.*

Heavy Lift Safety

- Plan the lift; know what an Installer are moving and where before lifting.
- Have two or more people carry panels in heavy winds to avoid accidents.
- Be sure the footing is stable.
- Lift with the legs by squatting so an Installer don't put added stress on the back.
- Avoid twisting while lifting and keep the weight close to the body.
- Ask for help when an Installer need it and wait for help when an Installer have to. If an Installer aren't sure whether an Installer can lift something alone, err on the side of caution.
- Use a hoist or crane to lift heavy equipment if necessary.

4.3 Wiring & Electrical

Wiring the electrical run is a critical part of any solar installation, and the specifics differ based on the kind of system you're installing. This section of the solar panel installation guide will outline how to plan the wiring run, ground the system, and install a backfeed breaker to connect to the utility grid if needed.

Wiring Management

Wiring management is an important (though often overlooked) consideration that will make the solar panel installation easier in the long run. Here are a few tips to keep in mind:

- Plan the wiring run in advance so the wires don't interfere with access to the array.
- Use wire clips to secure the factory wire leads in place so they don't move in the wind or touch the roof (required under the National Electric Code). Wire clips allow an Installer to run the wires along the rails or the frame of the solar panel.
- Many solar components use spring clamps, which require an Installer to push down on a metal bar (or another mechanism) to open the terminal so an Installer can seat the wire. Once the wire is firmly seated, release the spring, which clamps the wire in place.

Electrical Connection

The actual path of the wiring system will differ based on the type of system you're installing. Below are some summaries showing how wiring is connected for each system type:

Grid-Tie Wiring Path (Centralized SolarEdge / SMA Inverter)

- PV strings to junction box
- Junction box to inverter(s)
- AC Out to main/sub-panel

Grid-Tie Wiring Path (Enphase Micro-Inverters)

- PV panel to micro-inverter
- Micro-inverter to trunk cable
- Trunk cables to junction box
- Junction box to main panel

Off-Grid Wiring Path

- PV strings to combiner box
- Combiner box to charge controller(s)
- Charge controller(s) to battery bank
- Battery bank to inverter(s)
- Inverter(s) to load panel
- The generator also wires into the inverter (separate from the solar circuit)

Array Maps for Micro-Inverters/Optimizers

If the system uses micro-inverters or power optimizers, it's a good idea to make an array map that identifies where each device is located in the array. These products come with stickers, QR codes or other unique identifying markers. Attach these stickers to a piece of paper to make a map of the array.

During commissioning, plug this array map into the monitoring software to tell it the location of each panel in the array. This allows the software to properly monitor production and report defective equipment. Figure 5 shows an array map for micro-inverters/optimizers.

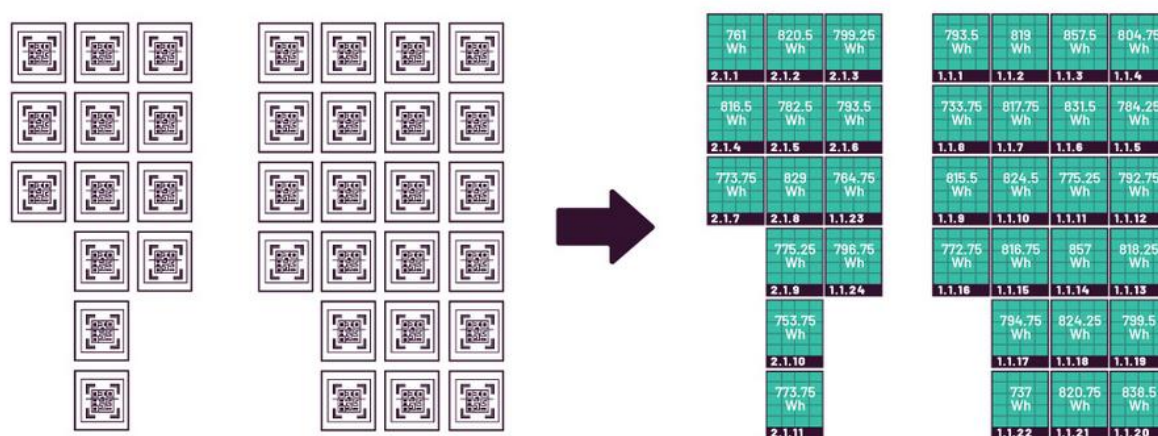


Figure 5. Array Maps for Micro-Inverters/Optimizers

Off-Grid DC Wiring

- Off-grid systems tend to have more wire terminations and work with higher amperages. Check all AC, DC, and communication connections to be sure everything is properly connected and torqued.
- Mark connections with a paint pen after an Installer tightens them so an Installer knows which connections have been torqued.
- If an Installer brings combined DC power from a solar panel array to a power center, take care to terminate the solar positive wire at the SOLAR INPUT (+) busbar, not the DC BATT (+) busbar.
- *Be careful not to confuse the solar input with the DC battery input.*
- After wiring, check terminals or busbars with a meter and determine they are operating at a safe voltage before proceeding with the rest of the build.

Planning Electrical Route

The Installer would want to plan the electrical run beforehand, taking into consideration which type of system you're installing. Again, safety is of the utmost importance: make sure an Installer wears the recommended protective equipment (gloves, eye protection, and closed-toe boots) and install the wiring according to the wiring diagram.

PV Sub-Panels

- Systems with multiple inverters can use an AC sub-panel to combine the AC circuits into a single set of conductors.
- Dedicated solar sub-panels must not contain any load breakers.

Roof Mount Electrical Route

- You can run the wiring through the attic to hide it from view, but make sure it is accessible to connect to the array, breaker box, panel, meter, and other parts of the system.
- Use cable clips to secure wiring from solar panels and micro-inverters/power optimizers. The clips should hold the wires in place during strong winds.
- Do not allow exposed wiring to make contact with the roof surface.
- Run the wiring from the solar source to a junction box, then transition to the conduit run. The wiring must remain in the conduit run until it reaches the inverter (for grid-tie systems) or charge controller (for battery-based systems).
- Use conduit mount flashings to secure rooftop conduit runs in place.
- If possible, use conduit penetration flashings to transition conduit into the attic to hide it from view.
- *A conduit run held in place by a Quick Mount conduit penetration flashing.*

Ground Mount Electrical Route

- Use cable clips to organize exposed wiring under the array. They should be secured against strong winds and kept out of the way so they don't interfere with maintenance.
- Call the local authority before starting any digging projects to avoid hitting buried gas or electrical lines.
- If an Installer uses a concrete truck or other heavy machinery, don't drive over any buried gas lines, plumbing, or septic systems that could be damaged.
- The wiring diagram will tell an Installer how deep to dig the trench, the size/type of wiring and conduit required, and the total distance of the run. It will also take voltage drop/voltage rise into account. Refer to it often as an Installer plans the run.

Mounting the Inverter

Inverter installation can look different depending on the solar system type. Inverters for grid-tie systems can be wall-mounted indoors, outdoors, or rigged on the back of a ground mount substructure. Off-grid inverters must be wall-mounted indoors.

Wall-Mounted Inverters (Grid-Tie & Off-Grid)

- Follow manufacturer guidelines for installation clearances to ensure that the equipment can cool effectively.
- Inverters with integrated disconnect switches must be mounted less than 2 meters (6.5 feet) off the ground. The exception to this is if the system design contains another switch that meets the AC disconnect requirements of the NEC (National Electric Code).
- If installed in a garage, any ignition source (inverters and disconnects) must be at least 18 inches off the ground.
- If installed outside, keep the inverter out of direct sunlight and clear of any sprinkler systems.

Inverters Mounted on Ground Mount Substructure (Grid-Tie Only)

- Mount the inverter higher than 36 inches off the ground to avoid mud splatter during heavy rains.
- Keep the inverter out of direct sunlight.
- Use threadlocker on the hardware that secures the inverter bracket to the support structure.

Grounding the System

Properly grounding the electrical components of the solar system is an essential step. For one, grounded electrical connections reduce the risk of shock, power surges, and build-up of static electricity. Moreover, if the circuit fails, grounding allows a safe pathway for fault current. Metal parts of an electrical system must be connected (bonded) to the ground, and conductive materials (EMT, metal boxes, etc.) must be grounded together. The latter ensures that each piece of equipment in the system shares the same resistance to the ground, or “ground reference.”

The following sections of our solar panel installation guide outline grounding methods and some extra tips to help an Installer ground the system properly.

EGC and GEC Grounding

- *EGC (Equipment Grounding Conductor)* is the green or bare copper wire that connects the racking hardware, metal enclosures, and EMT conduit together.
- *GEC (Grounding Electrode Conductor)* is the wire connecting the ground rod to the electrical distribution service. In most AC power systems, the neutral conductor has a single bonding point where it is connected to the ground.
- Neutral to ground bonds can be found in generators, breaker distribution panels, power centers, and other equipment. the system should only have a single neutral-to-ground bond.
- A DC negative to ground bond is necessary for any system. It is included with any system that features “ground fault protection.”

Integrated Grounding

- IronRidge’s UFO (Universal Fastening Object) and bonded fasteners make it so that an entire solar array can be grounded with a single grounding lug.
- Other mounts, like pole mounts, will not have integrated grounding solutions. Each panel and racking component needs to be grounded using UL listed grounding clips or lugs.

Backfeed Breaker Installation (Grid-Tie Only)

Grid-tie solar systems require a backfeed breaker, which is a device added to the main breaker panel. This enables the system to feed the power it generates into the utility grid.

A solar backfeed breaker is installed at the opposite end of the breaker panel from the grid input breaker. an Installer may need to re-arrange circuits in the breaker panel to put the solar breaker in the last position.

If an Installer need to make room for an extra breaker, Tandem Breakers make a single slot on the breaker panel that serves two circuits on the same phase (these are different from 120/240-volt multi-phase breakers).

How to Install a Backfeed Breaker

If you're not comfortable working on the breaker panel, don't be afraid to call a professional electrician. Many of our customers DIY their solar array and bring in a professional for the electrical work.

That said, if you're comfortable (and safe!) with this kind of work, here's a step-by-step outline of how to get a backfeed breaker hooked up:

1. Determine the proper breaker size and source a breaker that will work with the existing panel. It's ideal to use the same make and model as other breakers in the panel.
2. As an Installer work, stand on plywood or a rubber mat to insulate yourself from the ground. an Installer will want to gather insulated tools and a voltmeter with fresh batteries before an Installer begin.
3. Shut off the branch circuit breakers one at a time.
4. Shut off the main circuit breaker.
5. Remove the panel cover.
6. Test all the wires with a multimeter to make sure there's no current before proceeding.
7. Disconnect the wire of the breaker you're removing from the load terminal.
8. Carefully pull out the old breaker, paying close attention to how it's positioned.
9. Insert the new breaker and push it into position.
10. Attach the properly stripped solar circuit wires to the breaker terminals and torque into place.
11. Inspect the panel for any other problems. Tighten any loose terminals.
12. Replace the panel cover.
13. Turn on the main breaker.
14. Turn on the branch breakers one by one, leaving solar for last. Do not turn on the solar backfeed breaker until after inspection and interconnection agreement are completed.
15. Test the breakers with a multimeter to make sure everything works.

4.4 Mounting the Solar Panels

With a solid wiring & electrical plan in place, the next step is mounting the solar panels. Whether an Installer decide to roof mount or ground mount the array, the following sections will outline everything an Installer need to build a solid mounting foundation.

Roof Mounting

If an Installer decide to roof mount the solar panels, there are 5 main steps to take:

1. Locate and mark roof rafters
2. Install roof attachments to secure the rails in place
3. Install racking rails
4. Lift panels on to the roof
5. Mount panels on the rails

Step 1: Marking Roof Rafters

For a sturdy foundation, roof-mount flashings should be bolted to the roof rafters. There are a couple of methods for locating where exactly the rafters are:

Visual Location

Look for rafters under the eaves of the roof. If an Installer can't spot them, look for the nails that hold the fascia board and/or gutter to the ends of the rafters.

Echo Location

If it's safe, an Installer can get a feel for where the rafters are by walking around on the roof. The rafters will feel firm, while the space between them will feel a little spongy. an Installer can also use a rubber mallet to tap around on the roof and listen/feel for the rafters. This method is less effective on roofs with skip sheathing (a layer of boards that sit perpendicular to the rafters). The boards cover the rafters, which makes it difficult to know whether you've found a rafter or a skip sheathing board.

Exploratory Drilling

If none of the previous methods work, an Installer can drill exploratory holes in the roof to search for rafters.

- Start where an Installer plan to place the first flashing and drill a small hole in the roof.
- If the drill does not hit a rafter, bend a metal wire into an L shape and insert it into the hole.
- Rotate the wire to see if it hits a rafter.
- Once a rafter is found, measure 0.75 inches from the edge to the center of the rafter. Mark this location so an Installer can drill the lag bolt directly through the center of the rafter.
- If an Installer have attic access, an Installer can follow this process from the inside of the attic. Drill a hole on one side of the rafter, leaving the drill bit sticking through the roof so an Installer can locate it from the outside. Once an Installer climb on the roof, measure 0.75 inches from the drill bit to the center of the rafter to mark the location of the lag bolt.

Mark Rafters with Chalk Lines

Once an Installer mark both endpoints of each rafter, an Installer can connect them with a chalk line on top of the roof. This will give an Installer a visual indication of where to line up the flashings. The chalk will wash away the next time it rains, so don't worry about the lines being permanent.

- Attach the chalk line at the starting point of the line.
- Pull the string loaded with chalk out of the chalk reel.
- Secure the chalk line at the endpoint of the line.
- Use the finger to press the middle of the chalk line against the roof.
- Pull up on the line, then let go so it "snaps" against the roof. The impact will leave a temporary line of chalk for an Installer to work from. Do this on both sides of the point where an Installer are holding the line in place.
- Repeat until an Installer have marked the location of each rafter in chalk.

Step 2: Install Roof Attachments

With the location of the roof rafters marked, it's time to start installing the attachments that will secure the mounting rails in place.

Depending on the type of roof an Installer have, the process will differ, but we've included steps for the most common types below, along with some tips on spacing and layout for flashings.

Spacing and Layout Tips

The flashings should be spaced to align with the mounting holes on the solar panel. The distance between mounting holes will be listed on the panel spec sheet. Stagger the flashing layout so that they alternate between the top and bottom rail. Distribute the flashings evenly across all the roof rafters to spread the weight of the array across the entire mounting surface.

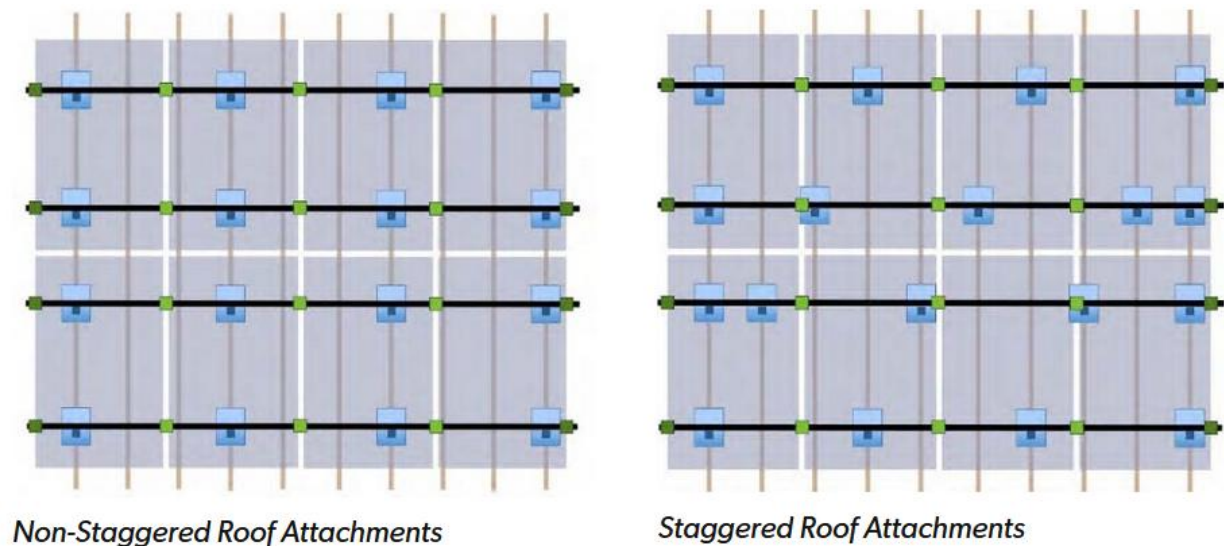


Figure 5. Layout for roof attachment

The layout on the left is more visually appealing, but all of the wind/snow load is concentrated on a few rafters. The staggered layout on the right makes for a more structurally sound array.

Composite / Asphalt Shingle Roof

Our systems commonly use the Ironridge Flashfoot 2 flashing system for composite/asphalt shingle roofs, so we've included installation instructions for that product here. If the system uses different flashings, consult the manufacturer's manuals for installation instructions.

1. Gently break the seal between the shingles with a flat bar.
2. Remove any nails that would prevent an Installer from sliding the flashing under the shingle.
3. Slide the flashing under the shingle, lining up the hole with the marked rafter.
4. Tuck the flashing into place. The bottom edge of the flashing should sit above the drip line (the bottom edge of the shingle). The top edge of the flashing should reach into the third course of shingles (see reference image).
5. Mark the drilling location through the hole in the flashing.
6. Remove the flashing and drill a pilot hole using a 7/32 inch drill bit. Double-check to make sure the hole is in a rafter.
7. Fill the hole with roof sealant and place the flashing.
8. Use an impact drill with a 1/2 inch deep socket to tighten to the flashing manufacturer's specifications.

Metal Roof

Metal rooftops use roof clamps that either attach onto a seam or bolt into the structure. There are dozens of clamp configurations and each one is a little bit different, depending on the rooftop. Check with the clamp manufacturer for specific installation instructions.

Tile Hooks

Tile hooks slide under the shingles and fasten to the rafters. A vertical hook provides clearance from the roof tiles. The racking rails bolt into slots in the tile hooks. Tile hook installation may require some cutting or grinding of tiles, but they are generally universal and work on most tile rooftops.

Tile Replacements

If an Installer bought a tile replacement system, an Installer will remove tiles on the roof and swap them out for the tile replacement flashing. A lag bolt is bolted to the rafter through the tile replacement, which serves as a foundation to attach the rails.

Ballasted Mounts for Low-Slope/Flat Roofs

Ballasted mounts do not require an Installer to make penetrations in the roof—the weight of the racking base and the array itself holds the system in place. Ballasted mounts only work on flat or low-slope roofs. Higher tilt angles mean less downward force holding the array in place, which makes them ineffective on steeper rooftops.

Step 3: Install Racking Rails

With the flashings in place, you're ready to attach the racking rails. Be sure to keep the Racking Report handy during this step—it specifies rail size and spacing for the system.

- Measure and cut the rails on the ground so an Installer don't get metal shavings on the roof.
- Rails should be spaced to match the distance between the mounting holes on the back of the solar panel frame. The flashings need to match this spacing as well.
- Use the supplied hardware to attach the rail to the flashing. (Pro tip: install the lower rail flashings on the upslope side of the rail so that the array hides the flashings from view.)
- Use a level to ensure the rails are even. The slots in the L-feet allow for vertical adjustment if needed.
- Tighten rails with a quality torque wrench according to the manufacturer's torque specs.
- Attach plastic end caps to keep spiders, bees, and other critters out of the rails.
- Attach wire management clips and any hardware for micro-inverters/optimizers to the rails.
- Install grounding equipment as an Installer install the rails. IronRidge systems contain one grounding lug per array.
- When starting a new row, leave space to account for the panel overhang on both sides, as well as a ½- to 1-inch clearance gap between the panels.

Step 4: Getting Panels on the Roof

Remember: **safety first!** As an Installer prepare to move the panels onto the roof, keep in mind the safety procedures outlined in the Planning & Safety section of this guide. Be sure to wear protective equipment, use fall protection, and never stand on panels or lift them by the electrical wires.

If an Installer want, an Installer can wrap the panels in a blanket to protect them from hard surfaces as an Installer move them.

Lifting Methods

Chances are, you'll want to rent some equipment to help lift the panels on the roof. There are a few options to choose from:

Ladder Lift: A ladder with a conveyor belt mechanism on it to help move heavy objects up and down the ladder.

Scissor Lift: A lift which extends up and down, as well as side-to-side. The horizontal movement means an Installer can take fewer trips from the ground to the roof and then back again.

Boom Lift: A lift with a full range of movement, giving an Installer access to tight spaces. Useful to get over and around obstacles that prevent an Installer from parking a lift directly under the spot where an Installer plan to install the panels.

Scaffolding: Scaffolding works great if there are no obstacles and an Installer don't need lift assistance. There's no mechanism to make lifting easier, but it does offer a sturdy platform to work on and some extra fall protection. Scaffolding provides a platform to stage materials and walk freely around the roof.

Step 5: Mounting Panels

Now that you've got the installed racking and panels in the same place, an Installer can finally put the two together and mount the panels!

The instructions outlined below use the IronRidge racking system (XR10, XR100, and XR1000), which comes standard with all of our packages, as an example. If an Installer purchased a specialty mount (like a pole mount), consult the product manual for instructions on how to mount the panels.

1. Place the panel so the mounting holes line up with the rails.
2. Use the IronRidge UFO (Universal Fastening Object) clamps to secure the panel in place. Start with the end on the outside edge of the array and drop the T-bolt in the slot in the rail.
3. Torque the UFO clamps with stopper sleeves (one in each rail) so they are snug against the outside of the first panel, locking it into place.
4. Slot the next pair of UFO clamps on the inside edge of the first panel.
5. Place the next panel on the rails, so that the clamps are wedged snugly between both panels.
6. Tighten the clamps between the panels.
7. Repeat this process for each panel in the array. Use the UFO with stopper sleeves attachment to secure the final panel in the row.

Ground Mounting

If an Installer decide instead to ground mount the solar panels, there are 3 key steps:

1. Build a foundation
2. Install racking railing
3. Mount panels on the rails

Step 1: Building a Foundation

Though ground mounting is quite a bit different from roof mounting, some of the same principles apply. First, you'll want to construct a solid foundation upon which you'll mount the racking rails.

Our ground mount racks use the IronRidge Ground Mount system. We provide an engineering report that specifies how deep and wide to dig anchor holes, pier spacing, and placement, as well as how much concrete and pipe to buy.

Follow the specs outlined in the Engineering Report (provided by Unbound Solar[®]) to ensure the structural integrity of the ground mount.

Pouring Concrete & Setting Piers

Always use proper protective gear (outlined previously in Planning & Safety) when working with concrete. Wet concrete will cause serious burns if exposed to the skin for prolonged periods. In addition, a respirator with a minimum rating of N95 is required when working near concrete dust.

Bearing safety precautions in mind, here are some guidelines for pouring concrete & setting up piers.

- Check if the site is level. Considering leveling the grade if necessary.
- Use chalk or a string line to mark the outer dimensions of the array and the locations of the piers on the ground.
- Call the local authority to locate buried power lines and septic systems before an Installer dig. Do not drive heavy machinery (like a cement mixer) over the buried lines.
- Carefully follow the pier placement and hole depth/width outlined in the engineering report.
- Create a temporary lumber substructure to keep piping in place while the concrete hardens. If pipes move before the concrete is fully cured, that can compromise the structural integrity of the mount.
- Underground pipe should be fully suspended in concrete. If the pipe touches the dirt, it can cause galvanic corrosion that will detract from the strength of the structure.
- Get everything else in place before an Installer mix the concrete. Once the concrete is wet, an Installer won't have time to adjust forms and make changes.
- Wait at least a week between setting piers and building the rest of the array. Concrete will take up to 21 days to fully cure. Leave the wooden brace in place until the concrete is fully cured.

Step 2: Installing Racking Rails

Your Racking Report will specify rail size and spacing for the system. Keep it handy during this step.

- Space the rails to match the distance between the mounting holes on the back of the solar panel. the racking report has the exact measurements.
- The Ironridge Ground Mount system uses a rail connector bracket which attaches the rails to the horizontal support pipes using U-bolts.
- When starting a new row, leave space to account for the panel overhang on both sides, as well as a ½- to 1-inch clearance gap between the panels
- *IronRidge rail connectors secure the rails to the support beam anchored in the ground.*

Step 3: Mounting Panels

With the racking rails installed and housed in a solid concrete foundation, the panels are ready to be mounted.

The instructions provided below use the IronRidge ground mount racking system as an example. If an Installer purchased a different racking solution (such as a ground mount system from Unirac), consult the product manual for instructions on how to mount the panels.

1. Place the panel so the mounting holes line up with the rails.
2. Use the IronRidge UFO (Universal Fastening Object) clamps to secure the panel in place. Start with the end on the outside edge of the array and drop the T-bolt in the slot in the rail.
3. Torque the UFO clamps with stopper sleeves (one in each rail) so they are snug against the outside of the first panel, locking it into place.
4. Slot the next pair of clamps on the inside edge of the first panel.

5. Place the next panel on the rails, so that the clamps are wedged snugly between both panels.
6. Tighten the clamps between the panels.
7. Repeat this process for each panel in the array. Use the UFO clamps with stopper sleeves to secure the final panel in the row.

4.5 Solar Battery Installation

If you're installing an off-grid system (or a grid-tie system with a battery backup) the last step of installation for the system will be to install a battery bank.

There are **three** types of batteries used in solar storage systems:

- Flooded Lead-Acid Battery
- Sealed Lead-Acid Battery
- Lithium-Ion Battery

Each of them has unique requirements in terms of installation and battery room design, detailed in the sections below.

Lastly, the Installer should consult the manufacturer's installation instructions and datasheets for important installation instructions. We have provided some general guidelines in this solar panel installation guide, but each manufacturer does things a bit differently, so it's best to refer to their specific guides when in doubt.

Safety Tips

As with every step of the solar panel installation process, proper safety precautions should always be taken. Before working with batteries, review the following safety guidelines:

Safety Guidelines for All Batteries

- Be careful to never short-circuit a battery! A short circuit occurs when the positive and negative terminals of a battery are connected together, either from improper wiring or when a metal object falls onto the battery terminals. Use insulated tools and be cautious to avoid short circuits.
- Remove all metallic jewelry, including watches and rings. Secure any long hair and avoid loose-fitting clothing that could get caught on wires or terminals.
- Always wear protective gloves and safety goggles when working with the batteries.
- Keep a multimeter with fresh batteries on hand. Use it to check conductors to verify voltage and polarity.
- Ensure that all wires are stripped and/or terminated properly using a torque wrench/driver when necessary.
- Route all wires away from sharp edges and pinch points that could penetrate and damage the wire.

Additional Safety for Flooded Lead-Acid Batteries

- Keep baking soda and an eye-wash kit on-hand. Baking soda is used to neutralize acid spills.
- Always wear nitrile gloves and safety goggles when working with flooded lead-acid batteries.

Battery Room Designs

Your battery bank should be installed in an enclosure to limit accidental contact with the batteries. The enclosure should allow for ventilation and leave enough space for batteries to

cool effectively. While an Installer will need to consult the wiring diagram and manufacturer's manuals for specific installation instructions, this section contains broad advice about designing and installing a safe enclosure for each kind of battery bank.

Sealed Lead-Acid & Flooded Lead-Acid Battery Room Design

Heat has a major impact on battery lifespan. While batteries can safely operate in a broad temperature range, the ideal ambient temperature for the battery bank is 77°F.

Prolonged exposure to higher temperatures will shorten battery lifespan, while lower temperatures reduce battery capacity. Install the battery bank in a temperature-controlled environment to keep them as close to the target temperature as possible. Natural fluctuations in room temperature based on time of day and seasonal factors are perfectly acceptable. The main concern is prolonged exposure to extreme temperatures. Batteries lose half their lifespan for every 15°F of continuous exposure over the ideal temp of 77°F. The battery bank should be built in a well-ventilated, temperature-controlled environment. At least, 1" of clearance should be left between each battery.

Considerations for Sealed Lead-Acid Battery Rooms:

- Keep a whiteboard or notepad in the room to record battery data during maintenance checks. an Installer can also use the Battery Maintenance Log provided at the end of this solar panel installation guide.
- Sealed lead-acid batteries do not off-gas as a normal part of operation, but they still have valves that will open if they are overcharged or overheated.
- Make sure the floor is structurally sound and can hold the weight of the batteries.

Considerations for Flooded Lead-Acid Battery Rooms:

- Flooded lead-acid batteries should be installed over a spill containment tray.
- Keep a whiteboard or notepad in the room to record battery data during maintenance checks.
- Flooded batteries off-gas hydrogen when they are charging and must be installed in a properly vented battery enclosure that is built according to fire and electrical codes. Consider buying a hydrogen gas monitor and don't keep anything in the room that could ignite the gas.
- Make sure the floor is structurally sound and can hold the weight of the batteries.

Lithium-Ion Battery Room Design

Temperature can have a major impact on battery performance. Li-ion batteries can be sensitive to extremely cold temperatures and typically cannot handle being charged below freezing (32°F/0°C).

Check the battery manufacturer's guidelines on the acceptable temperature range for charging and discharging the batteries. Install batteries in a temperature-controlled environment to keep them within the recommended operating range.

Considerations for Lithium-Ion Battery Rooms:

- Keep a whiteboard or notepad in the room to record battery data during maintenance checks.
- Make sure the floor is structurally sound and can hold the weight of the batteries. If mounting on the wall, make sure the wall is structurally sound to support the load.

Battery Bank Installation

Unsurprisingly, battery bank installation methods will be different depending on type and manufacturer. Included below are some general guidelines to follow while installing the batteries, arranged by battery chemistry.

Sealed Lead-Acid Battery Installation

- Though the batteries are sealed, they may release a small amount of flammable gas if overcharged/overheated. Do not install it close to electrical equipment or appliances that could discharge sparks.
- Batteries should be well-ventilated to keep them in a safe temperature range. Ventilation and other installation requirements for battery systems are covered under NEC article 480.10.
- The battery case should not come in contact with organic solvents or adhesive materials.
- Use UL-listed terminal lugs on battery interconnects, crimped according to the manufacturer's guidelines.
- Leave at least 1 inch of space between each battery to provide adequate ventilation and cooling.
- If the batteries will be subject to vibration (for example, in an RV system), fasten the battery bank securely and consider using shock-absorbent material inside the enclosure.
- Do not attempt to dismantle or touch the inside of the battery! Sealed lead-acid batteries will not leak under normal conditions, but they could spill if they are damaged. If accidental contact is made with the electrolyte, wash the affected area with liberal amounts of water, and seek IMMEDIATE medical attention.
- Baking soda can be used to neutralize small acid spills.

Ventilating Sealed Lead-Acid Batteries

Sealed Lead-Acid Batteries do not off-gas as a normal part of operation. However, they still have vents to relieve internal pressure in case of overcharging. If the battery is exposed to overheating, excessive voltage or current, it will release gas.

Though off-gassing is rare for sealed batteries, it could still happen in a worst-case scenario. Because off-gassing is possible, the battery enclosure needs to be ventilated properly. In many cases, building codes will apply the same requirements as they do for flooded lead-acid batteries.

Your vent should be at the top of the battery enclosure at the highest point so the hydrogen can escape. Seal any conduit to prevent hydrogen gas from going through the conduit and into the inverter and other equipment. Also, be sure there is nothing blocking the vents so that air can circulate freely.

Flooded Lead-Acid Battery Installation

- Wear nitrile gloves while installing or maintaining the batteries to prevent exposure to the battery electrolyte.
- Batteries should be well-ventilated to keep them in a safe temperature range and prevent the buildup of hydrogen gas. Ventilation and other installation requirements for battery systems are covered under NEC article 480.10.
- The battery case should not come in contact with organic solvents or adhesive materials.
- Use UL-listed terminal lugs on battery interconnects, crimped according to the manufacturer's guidelines.
- Leave at least 1 inch of space between each battery to provide adequate ventilation and cooling.
- If the batteries will be subject to vibration (for example, in an RV system), fasten the battery bank securely and consider using shock-absorbent material inside the enclosure.

- Do not attempt to dismantle or touch the inside of the battery! Battery acid will burn the skin. If accidental contact is made with the electrolyte, wash the affected area with liberal amounts of water, and seek IMMEDIATE medical attention.
- Baking soda can be used to neutralize small acid spills.

Ventilating Flooded Lead-Acid Batteries

Flooded lead-acid batteries off-gas a small amount of hydrogen gas as a normal part of their operation. The battery room must be well-ventilated to keep the Hydrogen gas levels below a safe threshold (less than 1% concentration by volume).

Battery rooms should be ventilated at a minimum rate of 1.5 cubic feet per minute. Make sure there is nothing blocking the vents so that air can circulate freely. Larger systems will typically use a battery vent fan to actively expel gases.

Since hydrogen gas is lighter than air, it will rise up in the enclosure. the vent should be at the top of the battery enclosure at the highest point so the hydrogen can escape. Be sure to seal any conduit to prevent hydrogen gas from going through the conduit and into the inverter and other equipment. Hydrogen gas is very corrosive and flammable in high concentrations, which makes proper ventilation extremely important.

Lithium-Ion Battery Installation

- The battery case should not come in contact with organic solvents or adhesive materials.
- Use UL-listed terminal lugs on battery interconnects, crimped according to the manufacturer's guidelines.
- Leave at least 1 inch of space between each battery to provide adequate ventilation and cooling.
- If the batteries will be subject to vibration (for example, in an RV system), fasten the battery bank securely and consider using shock-absorbent material inside the enclosure.
- Do not attempt to dismantle or touch the inside of the battery! Follow the manufacturer's guidelines for any troubleshooting procedures.

Battery Wiring

With the batteries safely installed in a suitable room, all that's left to do is wire them together. As with installation, The Installer should be sure to follow the wiring instructions provided by the manufacturer of the batteries. However, there are some general rule-of-thumb guidelines that is recommended:

For wires connecting the battery bank:

- All interconnection cables should be the same wire size and length.
- Do not place anything between the battery terminal and the ring terminal of the interconnect cable.
- Make sure all connections are torqued properly. Re-check them when an Installer perform battery maintenance to make sure they are secure. Connections that are loose or excessively tight can cause melted battery terminals and other failures.

For wires running from the battery bank to the inverter(s):

- Keep the battery bank and inverter as close together as possible.
- Positive and negative cables must be of the same length.
- Positive and negative cables should be zip tied together every 18 inches and installed in the same conduit to maintain maximum surge capability and reduce electromagnetic interference.
- Route the cables so that they do not interfere with the ventilation of the battery enclosure.

5. CONCLUSION

Solar photovoltaic systems have emerged as a clean, reliable and cost-effective alternative to fossil-fuel-based energy sources. This paper has provided a detailed examination of solar energy benefits, system components, wiring methods, safety procedures and installation techniques. Literature findings confirm that solar power reduces greenhouse gas emissions, enhances energy independence and offers long-term economic advantages. The successful installation of a solar PV system depends on careful planning, appropriate component selection, correct mounting, and strict adherence to electrical and safety standards. Regular maintenance—including cleaning, monitoring, battery inspection, and professional servicing—ensures that the system operates efficiently for many years. As renewable energy technologies continue to advance, solar PV systems will play an increasingly vital role in promoting environmental sustainability, improving household energy supply, and reducing dependence on non-renewable resources.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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CLIMATE CHANGE MITIGATION AND ADAPTATION IN NIGERIA: A COMPREHENSIVE REVIEW OF IMPACTS, STRATEGIES, POLICIES, AND LOCALLY-LED RESPONSES

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ABSTRACT

Nigeria faces increasing vulnerability to climate change despite contributing minimally to global greenhouse gas emissions. As Africa's most populous nation and a major oil-producing economy, Nigeria is confronted with rising climate-induced disasters, persistent poverty, food insecurity, environmental degradation, and economic instability. This technical paper reviews the evolution of climate change research in Nigeria, synthesizing findings from mitigation and adaptation studies published between 1999 and the present. Using targeted keywords to identify literature in Scopus and Google Scholar, the review shows an exponential increase in publications, with 75.2% focusing on climate change adaptation strategies (CCAS), 19.6% on mitigation strategies (CCMS), and 5.2% addressing both. The findings reveal that agriculture dominates both mitigation and adaptation research, reflecting its centrality to livelihoods and vulnerability. Social adaptation measures (45%) and structural/physical strategies (42%) were the most studied, while institutional responses (13%) were significantly underrepresented, underscoring gaps in policy and governance research. Energy, agriculture, forestry, waste management, and industry were the key mitigation sectors analyzed.

The study highlights the growing burden of climate impacts—desertification, coastal erosion, flooding, health risks, displacement, and conflict—and evaluates Nigeria's policy frameworks such as the Climate Change Act (2021), National Adaptation Plan (NAP), Nationally Determined Contributions (NDCs), and large-scale projects including NEWMAP, ACRReSAL, and the Great Green Wall. Despite multiple initiatives, limitations persist in political will, financing, governance coordination, and community integration. The paper stresses the urgent need for Locally Led Adaptation (LLA) to bridge implementation gaps, empower vulnerable communities, and strengthen resilience. Findings demonstrate that education is the strongest determinant influencing the adoption of adaptation strategies in Nigeria. The study concludes that advancing climate action in Nigeria requires enhanced institutional capacity, increased domestic financing, stronger policy coherence, and integrated community-driven approaches. Future research must prioritize institutional adaptation, local resilience strategies, and evidence-based governance to effectively respond to Nigeria's rapidly escalating climate risks.

1. INTRODUCTION

Nigeria is the most populated nation in Africa, with an expected 211 million inhabitants according to the World Bank in 2021. The country is an oil producer, with crude oil constituting over 80 percent of exports, one-third of banking sector credit, and half of government revenue. Nigeria's debt-to-GDP ratio stands at 23.27% and is escalating each quarter due to increased borrowing and a stagnant economy. It holds a B' sovereign credit risk rating from Fitch Ratings. Economic growth has varied between 0.8% and 3.6% over the past five years, occasionally falling below zero. In 2020, the nation faced its most severe recession in two decades due to the COVID-19 pandemic, which disrupted global trade and caused a decline in oil prices. The GDP was valued at USD 440 billion (EUR 440 billion) or USD 2,085 (EUR 2,085) per capita in 2021. The unemployment rate is estimated at 33.3%, while the inflation rate is recorded at 20.5%. Approximately 54% of the population has access to electricity, leaving over 97 million individuals without it; access to clean energy is at 15%, indicating that nearly 180 million people lack modern and clean cooking technologies.

Nigeria is among the most susceptible nations to the effects of climate change. Therefore, it is essential to reduce emissions and adopt methods to address the effects of climate change. This study reviews publications on climate change mitigation and/or adaptation in Nigeria. The objectives are: to ascertain prevalent climate change adaptation strategies (CCAS) and their causes; and to determine the climate change mitigation methods (CCMS) extensively implemented to decrease emissions in Nigeria. Appropriate keywords were employed to search for publications in Scopus and Google Scholar. Our analysis indicates that from 1999 to the present, there has been exponential development in the volume of publications on CCAS and CCMS. A total of 75.2% of the publications focused on CCAS, 19.6% on CCMS, and 5.2% addressed both CCAS and CCMS. A significant number of the papers on CCMS focused on 'Energy' and 'Agriculture.' Additional sectors found from the included research relevant to mitigation in Nigeria were 'forestry', 'waste management', 'industry', and others. Approximately 80.7% of the CCAS papers pertained to 'Agriculture', indicating the sector in Nigeria where climate change adaptive ability is most critical. A total of 45% of the publications on CCAS addressed 'Social' adaptation, followed by 'Structural measures' at 42%, while 'Institutional' measures constituted the least at 13%. The limited quantity of publications on institutional CCAS underscores the necessity for additional research. Institutional measures, encompassing policies, legal frameworks, and economic assistance, are essential for fostering resilience against the impacts of climate change. The primary factor affecting the adoption of CCAS is 'Education.' The increased volume of publications on 'Agriculture' for both CCMS and CCAS highlights the sector's significance and the necessity to enhance its mitigation and adaptation methods. Our data and findings were compared and discussed in conjunction with analogous studies on CCMS and CCAS in Africa.

2. LITERATURE SURVEY

Human activities worldwide have elevated greenhouse gas emissions in the atmosphere, resulting in climate change. Climate change has induced several physical and biological transformations globally. Such changes pose risks to individuals, impact the food supply chain, and deteriorate the natural environment. African developing nations are more susceptible to climate change and lack the capability to enhance resilience and adjust accordingly. Empirical evidence indicates that Nigeria is currently confronting environmental issues resulting from the impacts of climate change. Approximately 6% of Nigeria's land area is susceptible to extreme weather occurrences, positioning the nation among the top ten countries most affected by climate change. Climate change results in extreme weather phenomena and unpredictable fluctuations in temperature and precipitation. These alterations have resulted in chronic

flooding, displacement of populations and settlements, and food insecurity; escalating desertification and drought across various climatic regions of Nigeria; the erosion of coastlines and fluctuations in water temperatures; the alteration of aquatic ecosystems; and heightened gender disparities and intra-gender inequalities, particularly affecting women. Some have also ascribed these socio-economic effects to a rise in communal tensions and violence Jellason et al, (2019).

Rural and impoverished areas have heightened susceptibility to climate change. This is due to the fact that rural communities predominantly participate in subsistence agriculture. Moreover, because to the inadequate living circumstances, those regions are more susceptible to environmental degradation and natural calamities. Climate change has been attributed to diminished harvests, thereby exacerbating poverty in rural populations. In Nigeria's Sahel region, around 30 hectares of agricultural land are lost each year due to desertification. Individuals in poverty are more vulnerable to climate change and may oppose some mitigation efforts if these endanger their economic stability Ajibade et al, (2014). The incidence of diarrhoea, measles, and malaria is increasing, attributable to climate variability (rising temperatures) and inadequate environmental conditions Oloukoi et al, (2014). Therefore, it is essential to comprehend the causes of climate change to formulate suitable mitigation and adaptation strategies. A significant portion of climate change research in Nigeria predominantly concentrates on assessing the sensitivity of various bio-geophysical system features, while neglecting socio-economic concerns. This has contributed to a fragmented evaluation of climate change impacts, resulting in insufficient understanding of the mechanisms and specifics of existing coping methods (mitigation and adaptation) Enete et al, (2012), Onyimalu et al, (2021).

In 2020, it was estimated that the total greenhouse gas emissions from Nigerian agriculture amounted to approximately 322,000 kilotons of CO₂ equivalent. Livestock constitutes 69.2%, rendering it the predominant source of greenhouse gas emissions in Nigeria's agricultural sector. Greenhouse gas emissions are anticipated to rise by 94% by 2050 (67.7 Mt CO₂-eq) compared to 2010 levels Diaha et al, (2021). Despite possessing extensive arable territory for crop cultivation, Nigeria imported over NGN 3.35 trillion worth of foodstuffs from 2016 to 2019, while exporting only NGN 803 billion during the same year. This indicates that Nigeria's agricultural imports are quadruple its exports [16]. While other causes contribute to the decrease in agricultural output, climate change is a critical element. Weather variabilities generated by climate change may further diminish the nation's agricultural output, resulting in increased imports and adverse trade balances. A multitude of studies has been undertaken regarding climate change mitigation and adaptation in Nigeria. Okon et al. (2021) performed a systematic review regarding the effects of climate change in Nigeria. Our work concentrates on identifying methods to mitigate and adapt to the impacts of climate change. Numerous research on adaptation in Nigeria appear to concentrate on the agriculture sector. Onyeneke et al. (2019) performed a systematic review regarding climate change adaptation within the Nigerian agriculture sector. Likewise, Ojo et al. (2022), Jellason et al. (2019), Ojo et al. (2022), Tarfa et al. (2019), and Ogunleye et al. (2019) investigated diverse adaptive capacities in agriculture. Nonetheless, our work diverges since it seeks to discover diverse adaptation capacities to climate change. Our analysis similarly utilised the International Panel on Climate Change (IPCC) classification of adaptation strategies (structural/physical, social measures, and institutional measures) (Noble et al., 2014) to delineate the research trajectories of the incorporated CCAS papers. It is essential to identify research gaps and provide guidance for future research and policymaking. Moreover, numerous studies have examined the potential of various sectors for climate change mitigation. Elum and Momodu (2017), Dioha et al. (2020),

Abiodun et al. (2012), Adeoti et al. (2014), Okoroh et al. (2016), Chenge et al. (2018), and Arimi et al. (2014) investigated agricultural potential for climate change mitigation, whereas Ukoba et al. (2020), Enongene et al. (2019), Elum et al. (2017), and Giwa et al. (2017) examined the potential of renewable energy for climate change mitigation in Nigeria. Etermire (2021) concentrated on the significance of legal mechanisms in the implementation of mitigations. Our analysis amalgamated findings from the included research to present a comprehensive collection of instruments for climate change mitigation in Nigeria, facilitating evidence-based decision-making and policymaking. The studies included (for mitigation and/or adaptation) utilised either primary or secondary research methods; our study, which is secondary research, produced both quantitative and qualitative data to synthesise from the existing body of knowledge and contribute to climate change development in Nigeria.

Given the exponential population growth alongside diminishing resources, an escalation in poverty, food insecurity, and ecological disasters is unavoidable. Consequently, it is essential to reassess the existing mitigation, adaptation, and coping measures to develop resilient and effective responses to the impacts of climate change. Consequently, this study seeks to examine the subsequent enquiries:

- a. What are the factors and frequently utilised CCAS in Nigeria?
- b. What mitigating actions are being implemented to decrease GHG emissions in Nigeria?

This study is significant as it assesses prior and contemporary research methodologies, which are informed by knowledge and data, to identify the principal factors influencing mechanisms for mitigating, adapting to, and coping with climate change.

3. EFFECTS OF CLIMATE CHANGE AND SUSCEPTIBILITY

Climate change is perceived to disproportionately impact Africa, with the rate of temperature increase and its associated consequences, including desertification, coastal erosion, biodiversity loss, and saltwater intrusion, escalating more rapidly than the global average. In 2016, Verisk Maplecroft designated Nigeria as the seventh most vulnerable country worldwide. Likewise, in 2021, Nigeria's susceptibility to climate disasters and its adaptive capabilities were ranked 161 out of 182 countries evaluated by the Notre Dame Global Adaptation Initiative (ND-GAIN). Nigeria is especially vulnerable to climate impacts due to its substantial population, extensive coastline, insufficient resources for effective climate financing from both public and commercial sectors, and a deficiency in adaptation knowledge.

The nation is presently confronting issues characterised by intricate direct and indirect effects, including food insecurity, forced relocation, violence, adverse health consequences, and additional factors, which collectively impede climate action and economic development. Droughts and desertification in the dry and semi-arid regions of northern Nigeria have adversely impacted local people reliant on rain-fed agriculture. Droughts and desertification are causing nomadic pastoral populations to migrate from north to south, leading to conflicts with indigenous agricultural communities over dwindling resources. These nomadic cattle herders also introduce zoonotic infections that may be intensified by climate change.

Since 2012, the nation has experienced climate variability and intense rainfall in its central and southern regions, resulting in recurrent flood disasters with total losses and damages approximating USD 16.9 billion (EUR 16.9 billion). Presently, floods (both riverine and urban) and other climate-change-related calamities are contributing to a rise in disease prevalence, predominantly vector-borne diseases like malaria, which accounted for 200,000 fatalities in

2021, representing 32% of global malaria deaths, and impacted approximately 60 million Nigerians. Additionally, there is an escalating threat of waterborne diseases such as cholera. In several regions of the country, a confluence of droughts, saltwater intrusion, and sea level rise has negatively impacted agricultural production and urban infrastructure, resulting in increased food prices, development costs, and other associated consequences. Crop yields are highly susceptible to fluctuations and climatic variations due to numerous influencing factors, with agriculture predominantly reliant on rainfall; merely 1% of arable land is irrigated nationwide, while over 70% of farmers participate in subsistence agriculture, contributing nearly 23% to GDP. Econometric assessments project that Nigeria could incur losses ranging from USD 100 billion (EUR 100 billion) to USD 460 billion (EUR 460 billion) if it does not sufficiently adapt to climate change by 2050.

These vulnerabilities persist, adversely affecting the lives and livelihoods of Nigerians, despite Nigeria's status as a signatory to the Sendai Framework for Disaster Risk Reduction 2015 – 2030 (SFDRR). The Sendai Framework aims to substantially mitigate disaster risks and losses in lives and livelihoods, enhance community and national health, and foster resilience to disasters by prioritising the understanding of disaster risk and the fortification and investment in disaster risk governance. This initiative aims to diminish mortality, direct economic losses, and damage to critical infrastructure while significantly improving global collaboration and access to early warning systems. The discrepancy between ongoing vulnerabilities and adherence to the Sendai Framework suggests a disconnect between signed agreements and the adequacy of projects executed nationwide.

Nigeria's climate change adaptation methods encompass a multi-tiered strategy, incorporating national regulations such as the Climate Change Act 2021 and the National Adaptation Plan (NAP), with a current focus on locally-led adaptation (LLA) to incorporate community-based activities. Initiatives encompass the advancement of ecosystem-based adaptation, the promotion of sustainable agriculture and land utilisation, the enhancement of water management, and the transition to renewable energy sources. Essential strategies are being formulated to mitigate specific effects such as desertification, coastal erosion, and flooding through initiatives including erosion-resistant afforestation, water conservation, and enhanced irrigation and water storage techniques.

4. NATIONAL STRATEGIES AND POLICIES

The Climate Change Act 2021 establishes a legal foundation for climate action, in conjunction with other policies such as the National Adaptation Plan (NAP) Framework. The national policy emphasises critical sectors such as agriculture, forestry, land utilisation, food security, health, energy, transportation, waste management, and water and sanitation. *"Whole-of-Society" Approach:* The revised Nationally Determined Contributions (NDCs) implement a collaborative strategy, engaging government ministries, the commercial sector, civil society, and local governments.

5. PRINCIPAL INITIATIVES AND PRACTICES

Ecosystem-Based Adaptation encompasses nature-based solutions such as the cultivation of erosion-resistant trees on slopes and gullies, and the implementation of sustainable land management practices.

Sustainable Agriculture: Advocating for measures like conservation agriculture to enhance resilience to fluctuating climatic conditions.

Water Resource Management: Strategies encompass deepening boreholes, conserving groundwater, and instituting steps to avert flood inundation.

Renewable Energy: There is an initiative to augment the utilisation of renewable energy sources such as solar and wind power, along with enhancing energy efficiency.

Waste Management: Improving waste management systems is a crucial component of the national strategy.

5.1 Concentrate on Locally-Driven Adaptation (LLA)

Community Integration: A primary objective is to transcend a "top-down" methodology by incorporating community insights and objectives into national strategies and execution.

Empowering Local Communities: LLA seeks to enhance the autonomy of local communities in the formulation, oversight, and assessment of adaptation strategies pertinent to their unique needs and difficulties.

Illustration of Community Practices: In Anambra State, smallholder farmers are employing techniques like as planting erosion-resistant trees and erecting ridges to mitigate flood effects.

5.2 Challenges and Prospects

Implementation Deficiencies: Although national plans are established, there are deficiencies in execution, especially in incorporating local community demands and expertise comprehensively.

Requirement for study: There exists a continual necessity for study to comprehensively assess the status and efficacy of adaption initiatives and to improve forthcoming measures.

6.0 CURRENT STATUS AND TRENDS IN CLIMATE ACTION: POLICIES, STRATEGIES, AND IMPLEMENTATION FRAMEWORKS FOR ADDRESSING CLIMATE CHANGE.

In Nigeria, climate change adaptation is gradually becoming a significant area for intervention, with the capacity to enhance livelihoods, health, and foster resilient communities. The adaptation policies, laws, frameworks, and strategies of the Federal Government encompass Nigeria's revised Nationally Determined Contributions 2021 (NDCs), the 2021 Climate Change Act, the National Climate Change Policy, the National Adaptation Plan (NAP), the Long-Term Vision (LTV), the Medium-Term National Development Plan (MTNDP), the Biennial Update Report (BUR), along with additional national and sub-national plans. The NAP Framework serves as a precursor to the government's primary adaptation agenda, delineating its objectives to synchronise the nation's adaptation efforts with the Cancun Adaptation Framework. Additionally, the Framework offers guidance for developing adaptation practices that are consistent with Nigeria's economic objectives and context. The Framework encompasses other subsequent co-benefits and essential considerations, including community-based adaptation, ecosystem-based adaptation, a gender-responsive National Adaptation Plan process, and the acknowledgement of climate change as a pervasive issue with potential trade-offs. The Nigerian government has established a NAP framework, although there is no documentation regarding its application and implementation to mitigate vulnerability at the community level. Efficient adaptation delivery is crucial for Nigeria due to its vulnerability to climate extremes, and its minimal greenhouse gas emissions suggest that reduction, while significant, is a lower national priority than adaptation.

Governance of Climate Change

The government of Nigeria is structured into three levels: federal, state, and local governments. Local governments, as indicated by their designation, represent the most localised tier of

governance, engaging directly with grassroots communities. These local entities, together with their corresponding state governments, own ministries tasked with advancing pertinent development goals. Although these agendas may incorporate climate adaptation strategies via existing extension services, they frequently lack alignment with National Adaptation Plans (NAPs), suffer from inadequate funding, and are deficient in competent personnel.

The limited implementation of adaptation frameworks and instruments at the sub-national level results in the Federal Ministry of Environment overseeing the majority of projects, including those related to climate change adaptation and other environmental issues, even at the local level. Governance at the ministerial level is directed by a politically appointed cabinet minister, who is responsible for leading and collaborating with public workers in the Nigerian civil service at the Directorate level. The staff at that level encompasses inter-ministerial positions, diplomatic and climate negotiating duties, along with committees established at various national and sub-national tiers to address specific initiatives.

Climate Adaptation Initiatives in Nigeria

Nigeria is executing many climate adaption efforts, encompassing extensive activities such as The Great Green Wall and the World Bank-supported Nigeria Erosion and Watershed Management Project (NEWMAP). Other initiatives concentrate on particular sectors, such as the Yobe State Environmental and Climate Change Action Project, which advocates for resilient agriculture and alternative energy, and the Sokoto State healthcare effort aimed at constructing climate-resilient infrastructure. State-level initiatives are underway, such as the Lagos State Climate Adaptation and Resilience Plan (LCARP), alongside community-based programs and collaborations with the commercial sector.

Recent years have witnessed the most extensive adaptation projects in Nigeria, which include:

- a) The World Bank supported the Nigeria Erosion and Watershed Management Project (NEWMAP), developed in conjunction with the Federal Ministry of Environment, to address the issue of gully erosion in southeastern Nigeria and other types of land degradation in northern Nigeria. The project received approval in 2012, with the World Bank pledging around USD 500 million (EUR 500 million) to it. It consisted of three primary components: Gully Rapid Action and Slope Stabilisation (GRASS), (b) Integrated Watershed Management, and (c) Adaptive Livelihoods, and was executed in nineteen (19) states of Nigeria.
- a. The Building Nigeria's Response to Climate Change (BNRCC) project was a five-year initiative that commenced in 2007, focussing on research about vulnerability—both existing and future—alongside awareness and pilot programs, while integrating gender considerations throughout the project lifecycle. The BNRCC, costing USD 4.9 million (EUR 4.9 million), was financed by the Canadian International Development Agency (CIDA) and led to the formulation of the National Adaptation Strategy and Plan of Action on Climate Change for Nigeria (NASPA-CCN) in partnership with the Federal Ministry of Environment. The pilot projects were designed with the following objectives: employing enhanced varieties to bolster food security, supplying fuel-efficient wood stoves, introducing aquaculture as an alternative income source, reducing community reliance on forest products, enhancing access to water sources, and rehabilitating ecosystems through tree planting.
- b. The Great Green Wall is presently being executed throughout twenty-two nations, encompassing elements of forestry, water management, and energy. The primary objective is to cultivate 8,000 kilometres of forest across 100 million hectares of degraded land by 2030 to address ongoing droughts, food shortages, migration, and war. Initiated by the

African Union (AU), it is presently executed through a collaboration involving the United Nations Convention to Combat Desertification (UNCCD), the Food and Agriculture Organisation (FAO), the World Bank, the Global Environment Facility (GEF), the International Union for Conservation of Nature (IUCN), the Green Climate Fund (GCF), and various other entities. The project is projected to have accomplished 15% of its objectives and, once completion, will have resulted in the largest living system on Earth.

Additional projects and initiatives encompass the following:

- a. The African Development Bank (AfDB) has initiated the Africa Adaptation Acceleration Program (AAP), a USD 25 billion (EUR 25 billion) initiative in partnership with the Global Centre on Adaptation (GCA). The AAP will ultimately get funding from African governments, investors, foundations, resilience bonds, and debt-for-climate-adaptation swaps.
- b. Adaptation to climate change in the Lake Chad Basin, financed by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). The initiative aims to deliver adaptation solutions and optimal practices to 1,100 villages within the region and other nations. The five-year project conducted from 2013 to 2018 especially aimed at enhancing food security.
- c. The UK Foreign, Commonwealth and Development Office (FCDO) and the United States Agency for International Development (USAID) have contributed to the creation of knowledge products, country reports, climate risk resources, and research throughout Nigeria.
- d. In 2021, the World Bank initiated a successor to NEWMAP called the Agro-Climatic Resilience in Semi-Arid Landscapes (ACReSAL): This initiative is a \$700 million (EUR 700 million) endeavour aimed at enhancing landscape management in northern Nigeria. The project consists of four sequential components designed to tackle the issues of extensive watershed degradation in northern Nigeria, enhance community climate resilience, bolster institutional capacity, and establish a foundational framework for multisectoral integrated landscape management and climate resilience. Additionally, it aims to implement a financing mechanism accessible to borrowers in investment project financing operations, thereby facilitating the rapid allocation of uncommitted funds to address eligible crises or emergencies.
- e. *Sokoto State Climate-Resilient Healthcare Initiative*: A project aimed at establishing climate-resilient healthcare infrastructure, encompassing new medical faculties, a teaching hospital, and enhanced pharmaceutical supply chains.
- f. *National Adaptation Plan Framework (NAPF)*: A framework that directs the nation's adaptation initiatives, serving as the foundation for the government's primary adaptation agenda.
- g. The Bank of Industry (BOI) has received accreditation from the Adaptation Fund as a National Implementing Entity, allowing it to access and administer money for projects in areas impacted by climate change.

Projects tailored to certain sectors and communities:

- a. *Sustainable Agriculture for Climate Adaptation (SACA)*: Enhances the adaptive potential of children and youth in marginalised areas using sustainable agricultural methods.
- b. *Yobe State Environmental and Climate Change Action Project*: Facilitates resilient agricultural, alternative energy, and reforestation activities in Yobe State.
- c. *Kaduna State Climate Action Plan*: Encompasses initiatives to initiate renewable energy pilot projects, including solar mini-grids, and to execute waste management reforms.

- d. *Community-Centric Initiatives:* Programs emphasising local strategies, such as educating women in community monitoring and creating cost-effective clean cooking solutions.
- e. *Southern Niger Connectivity and Integration Project:* A transnational initiative featuring elements in northern Nigeria, designed to enhance infrastructure and foster resilience.

4. TRENDS AND ANALYSIS OF CLIMATE FINANCE

Financing adaptation is a paramount worldwide concern, and Nigeria is no exception. Climate adaptation initiatives in Nigeria have primarily received funding from foreign agencies, although being executed at both national and sub-national levels. Similar to many countries in Sub-Saharan Africa, Nigeria depends on external loans, assistance, and grants to fund over 50% of its climate adaptation and mitigation initiatives. A considerable portion of the project expenses is covered by multilateral financial institutions (MFIs), primarily the World Bank and, to a lesser degree, the African Development Bank (AfDB). Other significant international contributors to adaptation initiatives in Nigeria comprise GIZ, FCDO, and USAID. The financial contributions for adaptation from the Nigerian government and the business sector have not yet reached the necessary level to address the funding deficit related to enhancing resilience.

5. DEFICIENCIES AND LIMITATIONS OF EXISTING CLIMATE INITIATIVES

The primary obstacle to implementing climate change adaptation in Nigeria is the absence of the topic in the public discourse. The essential frameworks necessary for offering guidance and systematic support in the planning, implementation, and administration of adaptation practices are now in the early stages of development. In the lack of a widely recognised, if not universal, adaptation process, adaptation practices are marked by autonomous efforts from local communities, international groups, and governmental agencies.

A prevalent issue associated with climate adaptation in Nigeria is the insufficient political will to address it as a significant national priority, resulting in inadequate funding for such initiatives. Investment for adaptation from both public and private sectors is significantly inadequate to address the escalating risks of a climate emergency, even disregarding the fact that such investment is potentially unsustainable without the earlier construction of a robust framework. The lack of citizen advocacy for enhanced environmental governance is a constraining element. As previously mentioned, these demands have increased alongside heightened climate change knowledge nationwide, both of which are predecessors to the escalation of national political debates on adaptation.

Consequently, collaboration among ministries and government agencies with distinct responsibilities in climate change management is constrained, and science-based targets have not yet been sufficiently integrated to effectively guide planning and legislation. Moreover, communities typically lack access to financial resources (credit, insurance, and consulting services), sufficient environmental governance (an enabling policy framework, political commitment, subsidies, and incentives), enhanced agricultural inputs, energy, and equitable legal recourse. This absence of access represents a considerable limitation. The problems indicate the necessity for an alternative strategy regarding climate action, particularly climate adaptations, that corresponds with the needs and ambitions of Nigerians and influences overarching national policy priorities.

6. POSSIBLE FUNCTION OF LOCALLY DRIVEN ADAPTATION IN NIGERIA

The acknowledged constraints in resource distribution, along with Nigeria's significant susceptibility, underscore the necessity for effective comprehension and management of

climate adaptation. In summary, without a strong adaptation strategy for climate change, Nigeria's economic growth will achieve negligible progress, if any, and the nation will face several external challenges that may escalate into intricate social problems, affecting both regional and local spheres. Although numerous actors have formulated adaptation policies and implementation strategies, the sufficiency and efficacy of these measures remain unassessed in a manner that yields evidence for enhancement and comprehensive climate action, encompassing the acknowledgement, documentation, and incorporation of local perspectives and ongoing adaptation strategies and practices. The bottom-up methodology of Locally Led Adaptation (LLA) presents a tremendous opportunity to harness the potential and advantages of climate action in Nigeria, particularly at the local level, where such initiatives are critically required. Local Level Adaptation (LLA), characterised as community-driven adaptation aimed at achieving fair, efficient, and transparent outcomes, comprises eight principles established by the Global Commission on Adaptation in 2021, which serve as guidelines for its advancement. Fundamentally, these principles embody the notions of inclusivity for local stakeholders and marginalised groups, enhanced comprehension of climate risk, substantial and consistent funding, transparency, and collaboration. Nonetheless, it is imperative to comprehend the needs, priorities, and values of the local community to ensure alignment of these principles with the realities and aspirations of the target population.

The effects of climate change on the Nigerian economy and the anticipated escalation of adverse impacts on lives and livelihoods indicate that LLA offers the greatest potential for comprehensive and enduring solutions. LLAs offer numerous benefits, including enhancing lives and livelihood prospects, fostering resilient communities, and equipping them with the necessary tools and resources to thrive in a warming climate. An appropriately adjusted economy can recover more swiftly and yield greater returns for each dollar invested, perhaps reaching six dollars for dollar invested, as stated by the UN. These savings are crucial for financially limited countries like Nigeria. A well-adapted nation fosters a dynamic ecosystem for community prosperity by establishing businesses and livelihoods, implementing clean energy systems, addressing social issues and their root causes, promoting cleaner and safer environmental policies and regulations, thereby enhancing the overall wellbeing and life expectancy of the population.

7. PROSPECTIVE FUNCTION AND SIGNIFICANCE OF NOVEL RESEARCH TO AUGMENT ADAPTATION INITIATIVES IN THE NATION

Although LLAs may play a beneficial role for Nigerians, further research is essential to comprehend the existing adaptation policies and strategies within national and regional frameworks, as well as their execution at the local level. Understanding how local communities perceive and address the current effects of climate change is essential, as this knowledge can enhance, advance, and bolster existing local initiatives. Furthermore, this knowledge can serve as a catalyst to expedite national climate adaption efforts by aligning policies with the needs and interests of the majority of Nigerians.

The current research underpinning this working paper aims to produce insights that enhance policy coherence and integrate climate adaption measures by:

- a. Assisting both established and emerging participants in the Nigerian adaption sector;
- b. Assisting Nigeria in reconciling climate initiatives with objectives of economic advancement, employment generation, and sustainable economic growth.

Ultimately, all of the aforementioned factors play a crucial part in national development and economic success. Effective adaptation can diminish government expenditures, conserving

essential fiscal resources. For communities enduring severe conditions, beset by poverty and the looming threat of climate change, the implementation of efficient adaptation solutions with multifaceted objectives is exceedingly urgent. This study will serve as a reference for future initiatives to enhance LLA activities and inform subsequent research and actions on the subject.

8. CONCLUSION

This study reviewed and synthesized two decades of climate change mitigation and adaptation research in Nigeria, revealing both significant progress and substantial gaps in national climate action. The evidence shows that Nigeria is experiencing intensifying climate impacts—ranging from flooding, drought, coastal erosion, health crises, biodiversity loss, and food insecurity to conflict and displacement—while lacking adequate institutional, financial, and governance structures to address these challenges at scale. Although national frameworks such as the Climate Change Act (2021), the National Adaptation Plan (NAP), updated NDCs, and a suite of large-scale adaptation projects demonstrate the government’s recognition of climate risks, the translation of policies into effective local action remains limited.

The dominance of agricultural-focused studies reflects the sector’s heightened vulnerability and importance to livelihoods, yet the relatively low number of institutional adaptation studies signals a significant research and governance gap. Institutional actions—policies, regulatory mechanisms, planning frameworks, financing systems, and cross-sector coordination—are essential for long-term resilience but remain weak or insufficiently explored. The review further establishes that education is the strongest determinant influencing the adoption of adaptation strategies, highlighting the need for targeted awareness, capacity-building, and knowledge dissemination at the grassroots level.

The analysis also reveals that climate finance in Nigeria is overwhelmingly donor-dependent, with limited domestic resource mobilization and low private sector participation. This financing imbalance hinders sustainability, reduces national ownership of adaptation processes, and perpetuates implementation gaps. Climate adaptation governance at the federal, state, and local levels suffers from fragmentation, weak coordination, and inadequate political prioritization, further limiting the reach and effectiveness of climate initiatives.

Given these realities, the paper underscores the transformative potential of Locally Led Adaptation (LLA) as a pathway to achieving equitable, context-specific, and resilient outcomes. LLA offers an opportunity to elevate community knowledge, integrate indigenous coping mechanisms, improve project sustainability, and ensure that adaptation aligns with the priorities and realities of Nigeria’s most vulnerable populations. It also strengthens transparency, accountability, gender inclusion, and climate justice—core principles needed to operationalize effective adaptation at scale.

Ultimately, strengthening climate resilience in Nigeria requires a multi-pronged approach: enhancing institutional capacity, aligning national policies with local realities, increasing domestic climate financing, fostering stronger intergovernmental collaboration, and scaling nature-based and ecosystem-based solutions. Additionally, expanding research into underexplored sectors—particularly institutional adaptation, urban climate risks, and the socio-economic drivers of vulnerability—is essential. With coherent policies, targeted investments, empowered communities, and robust research, Nigeria can build a climate-resilient future that safeguards livelihoods, supports sustainable development, and ensures long-term national stability in the face of accelerating global climate change.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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SOLAR PHOTOVOLTAIC TECHNOLOGY: FUNDAMENTALS, SYSTEM DESIGN, AND DEPLOYMENT PROSPECTS IN AFRICA

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ABSTRACT

Solar photovoltaic (PV) technology has emerged as a critical component of global renewable energy transitions, with growing relevance within Africa's electricity sector. Despite historically limited deployment, projections indicate substantial expansion, with solar PV expected to contribute up to 7–8% of sub-Saharan Africa's total generation capacity by 2030 (International Energy Agency [IEA], 2014). This paper presents a comprehensive technical review of photovoltaic technology, covering fundamental operating principles, components, classifications of PV cells, and system configurations. It further examines utility-scale and rooftop PV systems, cost trends, performance metrics, environmental considerations, and socio-economic impacts. The review also evaluates design fundamentals, including solar irradiance, conversion efficiency, energy losses, degradation, and the performance ratio. Lastly, major project development requirements—ranging from feasibility studies to grid integration and economic assessment—are analysed. The study synthesises current knowledge to support planning, policy formulation, and technological deployment aimed at enhancing solar PV adoption across Africa.

1. INTRODUCTION

Solar photovoltaic (PV) systems have gained renewed global attention as countries strive to decarbonise their electricity sectors. In Africa, where energy access remains significantly constrained, PV technology presents a valuable opportunity to increase electrification, particularly in off-grid and rural regions. Historically, solar PV contributed minimally to sub-Saharan Africa's power mix; however, the Africa Energy Outlook projects its share to rise to 7–8% of generation capacity by 2030 (IEA, 2014). This transition is driven by declining PV costs, improved technological efficiency, favourable solar resources, and enhanced policy

support mechanisms.

PV technology spans a wide spectrum—from pico-solar home systems used for basic household services to large-scale utility plants exceeding 100 MW. Africa's favourable solar irradiance conditions, averaging between 2,000 and 2,500 kWh/m² annually in several regions, position the continent as one of the most promising markets for solar deployment (SBC Energy Institute, 2013). However, the effective use of PV systems requires a deep understanding of their fundamental principles, system components, design parameters, and implementation challenges.

This paper provides a technical overview of solar PV systems, encompassing their scientific basis, technological classifications, structural elements, economic feasibility, environmental implications, and socio-economic impacts. The discussion aims to inform engineers, energy planners, policymakers, and researchers seeking to advance sustainable solar deployment across Africa.

2. LITERATURE SURVEY

Solar PV technology relies on the photovoltaic effect, whereby semiconductor materials convert sunlight into electrical energy. PV modules consist of interconnected solar cells, generating direct current (DC), which may be converted into alternating current (AC) for grid applications via inverters. Commercial PV cell efficiency typically ranges from 16% to 22% for standard silicon modules, with advanced technologies achieving higher performance (Fraunhofer ISE, 2020). PV deployment in Africa has historically been limited; however, high solar resource availability and decreasing system costs have driven recent interest. The IEA (2014) emphasizes that PV's share in sub-Saharan Africa will continue to rise due to improved policies, reduced module prices, and increased experience in utility-scale installations.

Existing literature identifies four dominant PV technologies include; Crystalline silicon—monocrystalline and multicrystalline—dominates global PV markets due to high efficiency and reliability. Commercial monocrystalline cells achieve up to 22.5% efficiency, while multicrystalline modules achieve approximately 18% (Green et al., 2022).

Thin-film technologies—including CdTe, CIGS, and amorphous silicon—require less semiconductor material. Although thin-film modules typically exhibit lower efficiencies (10–13%), CdTe and CIGS technologies have achieved laboratory efficiencies exceeding 20% (NREL, 2021). Their lower production cost and superior performance under low-light conditions support their continued relevance.

CPV systems use optical lenses or mirrors to intensify sunlight onto high-efficiency multi-junction cells. Multi-junction cells have achieved efficiencies exceeding 35% (King et al., 2012), though CPV remains less common due to high cost and tracking system complexity. Organic PV cells use polymer-based materials with low manufacturing costs. However, their commercialization is limited due to lower efficiency, shorter lifetimes, and poorer structural stability (Brabec et al., 2018). A PV system typically includes modules, mounting systems, cables, charge controllers, inverters, and battery storage for off-grid applications (EnergyPedia, 2013). System performance depends on irradiance, temperature, module mismatch, wiring resistance, and inverter efficiency. Industry studies report standard inverter efficiencies of 96–98% (Spertino et al., 2015).

Africa's high solar irradiance (up to 2,500 kWh/m² in North Africa) enhances PV performance.

However, environmental conditions such as dust and high temperatures reduce efficiency and increase PV degradation (Huld et al., 2010). Utility-scale PV plants (10–100 MW) require large land areas (1.7–5 hectares/MW) and robust grid integration studies. Power Purchase Agreements (PPAs) and Feed-in Tariffs (FiTs) remain key regulatory mechanisms supporting grid-connected projects (REN21, 2021). Rooftop PV systems, facilitated by net-metering policies, offer decentralized electricity access and reduce reliance on diesel generators—common in African commercial and residential settings.

The cost of PV systems has declined dramatically, with module prices dropping by over 80% between 2009 and 2015 (SolarServer, 2015). Energy Payback Times (EPBT) range between six months and two years, depending on technology and location (Fthenakis & Kim, 2011). PV systems emit substantially fewer greenhouse gases than fossil fuel plants and contribute positively to climate mitigation efforts. Yet, environmental concerns persist regarding battery disposal, CdTe toxicity, and water consumption for module cleaning, particularly in arid regions (Peng et al., 2013).

PV systems significantly improve living standards in rural areas, enhancing access to lighting, education, healthcare, and economic activity. Organisational models vary—from community ownership to utility-led systems—with each presenting distinct advantages and operational challenges (World Bank, 2018).

3. FUNDAMENTAL PRINCIPLES

Photovoltaic systems (PV) consist of photovoltaic modules. The fundamental item in a photovoltaic module is the solar cell, which converts light into energy. The direct current (DC) generated fluctuates continuously based on the intensity of the incoming solar radiation. The current is also dependent on incoming solar energy. A photovoltaic module comprises several solar cells interconnected to attain an elevated voltage. A module for off-grid applications is often configured for a voltage of 12 V or 24 V, utilising 36 and 72 cells in series, respectively. In grid-connected systems utilising modules with elevated voltage and alternating current (AC), an inverter is required to convert direct current (DC) into alternating current (AC). The voltage must be transformed to a minimum of 230 V, contingent upon the linked system. When cells are assembled into a module, various losses diminish the module's efficiency relative to the cell efficiency.

Photovoltaics (PV) is among the most rapidly expanding renewable energy technologies and is anticipated to significantly contribute to the future global electricity generating portfolio. Photovoltaic technology can be implemented across several sizes, ranging from an integrated solar cell in a solar lantern to a battery-operated solar system for a residence or educational institution, and even to a big grid-connected solar power plant with a capacity of several megawatts. It is essential to note that the peak solar energy received at the equator is approximately 1000 W/m² during optimal sunlight hours (see to solar irradiance). Furthermore, the optimal efficiency now attainable for commercial solar panels ranges from 16% to 22%. Consequently, one square metre of photovoltaic panel can optimally yield an electrical capacity of 220W. Enhanced efficiencies can be attained through the utilisation of many layers inside a single cell or by focussing sunlight.

4. CLASSIFICATION OF PHOTOVOLTAIC CELLS:

Numerous photovoltaic technologies have been created over the years and can be categorised as follows:

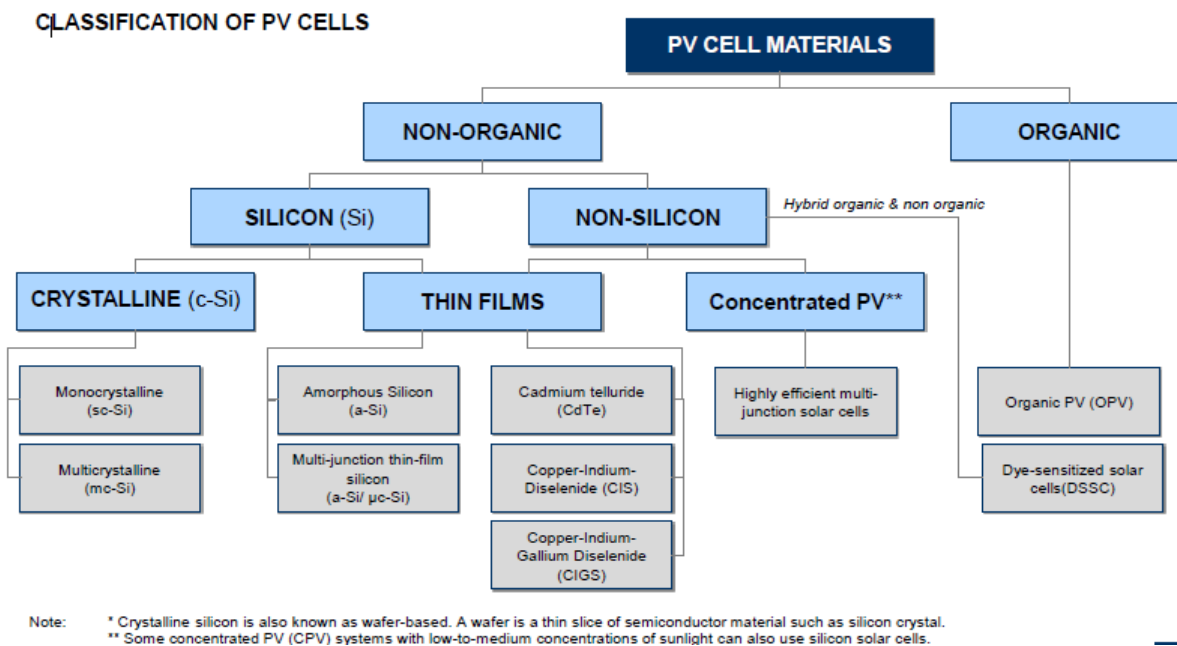


Figure 1. Classification of PV Cells:

Source: https://energypedia.info/images/4/41/SBC_Energy_Institute_Solar_PV_FactBook.pdf,

4.1 Crystalline silicon photovoltaic cells

This technique employs wafer-based crystalline silicon (c-Si) technology, specifically either single (monocrystalline, sc-Si) or multicrystalline (mc-Si). Crystalline silicon cells can be affixed to either framed or frameless panels appropriate for integration into roofs or façades. The current maximum cell efficiency for commercial monocrystalline cells is 22.5%, whereas multicrystalline cells achieve approximately 18% efficiency.

4.2 Thin-film photovoltaic cells

Thin-film technology minimises the material needed for the production of the active component in solar cells. The majority of thin-film solar cells are encapsulated between two glass panels to form a frameless module. Thin-film panels are nearly twice as heavy as crystalline silicon panels, as silicon solar panels utilise only a single pane of glass. The bulk of thin-film panels exhibit conversion efficiencies that are 2% to 3% lower than those of silicon panels. Cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (A-Si) represent three thin-film technologies. The maximum efficiency attained is approximately 20% with Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). The market share of thin-film photovoltaics constitutes around 11% of all produced photovoltaics.

5. CONCENTRATED PHOTOVOLTAIC TECHNOLOGY

Concentrating photovoltaic (CPV) systems employ optical instruments, such as lenses or mirrors, to focus direct solar radiation onto diminutive, extremely effective multi-junction solar cells. Commercial CPV modules utilising silicon-based cells exhibit efficiencies between 20% and 25%. Commercial multi-junction devices exhibit efficiencies of approximately 35%, markedly surpassing those of traditional single-junction crystalline silicon solar cells. Multi-junction solar cells comprise a series of stacked p-n junctions, each constructed from a unique combination of semiconductors, possessing varying band gaps and spectral absorption characteristics to maximise solar spectrum absorption. Multi-junction technology has lately

been commercialised and remains in limited output.

6. ORGANIC PHOTOVOLTAICS (OPV)

An organic solar cell, sometimes known as a plastic solar cell, is a variant of polymer solar cell that employs organic semiconductors. The plastic utilised in organic solar cells exhibits minimal production costs at huge volumes. Due to the adaptability of organic molecules, organic solar cells may be economically viable for photovoltaic applications. The primary drawbacks of organic photovoltaic cells include reduced efficiency, diminished stability, and inferior strength relative to inorganic photovoltaic cells. The market presently comprises just a limited number of firms. Currently, organic photovoltaics employ three principal technologies: 1. Oligomers of OPV 2. OPV Polymers 3. OPV DSSC (dye-sensitized solar cells; hybrid technology).

The details of the predominant applications for solar photovoltaic technology are as follows:

- *Utility-Scale Power Generation:* Large solar farms covering acres of land or floating on water generate power in the tens of megawatts to more than a gigawatt, feeding electricity into municipal or regional grids.
- *Residential and Commercial Buildings:* PV panels are commonly installed on rooftops to supplement power usage and reduce electricity bills. Excess energy can often be sold back to the utility grid.
- *Building-Integrated Photovoltaics (BIPV):* Solar materials are integrated into a building's structure, serving a dual purpose as architectural elements like windows, roof tiles, or cladding, as well as power generators.
- *Remote/Off-Grid Locations:* In areas where extending power lines is not cost-effective or feasible, PV systems provide stand-alone power for rural homes, telecommunications equipment, water pumps, remote health clinics, and street lights.
- *Space Applications:* From its earliest use, PV has been a primary power source for Earth-orbiting satellites, the International Space Station, and surface rovers on the Moon and Mars.
- *Transportation:* PV panels provide auxiliary power for vehicles like cars, boats, and high-altitude aircraft. They are used for onboard needs, such as charging batteries or powering specific functions.
- *Portable Electronics:* Small-scale PV cells are used in consumer products such as calculators, watches, flashlights, portable chargers for mobile devices, and integrated into items like backpacks or tents for off-grid power.
- *Agriculture:* Applications in farming include powering irrigation systems, water pumping, and agrivoltaics (combining solar generation with crop production on the same land).
- *Specialized Industrial Uses:* PV technology is used to power various stand-alone devices and tools such as temporary traffic signs, emergency phones, and for cathodic protection of pipelines to control corrosion.

Large-scale utility photovoltaic systems are engineered to deliver power to the electricity grid. The majority of contemporary solar power plants are owned by independent power producers (IPPs), however some are controlled by electric utilities. These facilities are typically constructed with capacities ranging from 10 to 100 MW and need extensive land expanses. To establish a backup generation facility, the plant is occasionally integrated with rapid-start and adequately adaptable diesel engines or open cycle gas turbines. Feed-in prices for electricity generated must range from 0.10 to 0.15 USD/kWh to achieve financial viability, contingent upon system size, solar resources, financing costs, and project hazards. The proprietor of a large-scale photovoltaic system must additionally secure a power purchase agreement (PPA)

when the energy is to be sent to the grid.



Figure 2. Large-Scale Utility-Scale Solar Energy Project

Source: <https://ratedpower.com/blog/benefits-utility-scale-solar-energy-projects>

Rooftop solar photovoltaic systems are typically linked to buildings, either incorporated into them, affixed to the roof, or situated on adjacent auxiliary structures. Building-integrated photovoltaic systems are progressively integrated into new residential and industrial structures as a primary or supplementary source of electrical energy. This market exists in numerous developing countries with elevated electricity rates, although remains unexplored in Africa. If the building cannot utilise all the energy generated by the photovoltaic system, the owner must establish an arrangement or Power Purchase arrangement (PPA) to sell the surplus energy to the grid.

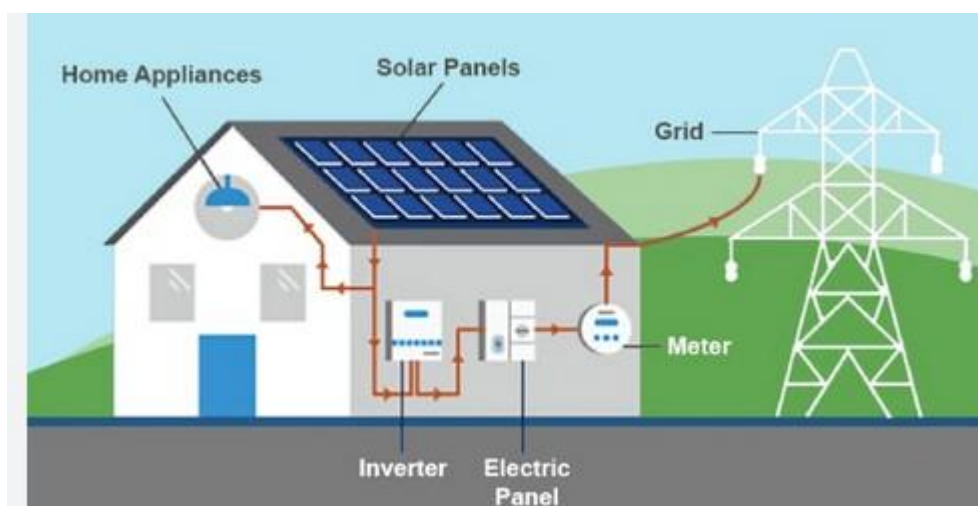


Figure 3.. Rooftop solar photovoltaic systems

Source: <https://gharpedia.com/blog/rooftop-solar-pv-system-basic-guide/>

Pico-PV and solar home systems have undergone considerable advancement in recent years, particularly in rural regions distant from the grid, integrating highly efficient lighting (predominantly LEDs) with charge controllers and effective batteries. A modest photovoltaic

module, generating only a few watts, can supply basic services such as illumination, phone charging, and radio operation. Expandable solar pico-systems have been introduced to the market. Rural households can initiate by purchasing a basic kit, subsequently augmenting it with a supplement, so enabling more lights and services to be connected, including the potential for a tiny television.



Figure 4. Pico-Scale Solar for Pico-Rural Growth in Africa

Source: <https://solarmagazine.com/pico-scale-solar-for-pico-rural-growth/>

7. OVERVIEW OF TECHNOLOGY

The primary elements of a solar photovoltaic system are:

- The photovoltaic module is a semiconductor that directly converts sunlight into electricity.
- The solar cables that connect solar modules and other electrical components within the photovoltaic system
- Mounting system - necessary for the installation of PV modules and additional components
- Batteries for electricity storage and energy provision on demand during nighttime or overcast conditions; typically utilised exclusively in stand-alone systems. Inverters are necessary to transform the direct current (DC) generated by the photovoltaic (PV) module into alternating current (AC) electricity, applicable for grid connection or a 230 V system.
- Controllers that regulate energy storage to the battery and supply power to the load

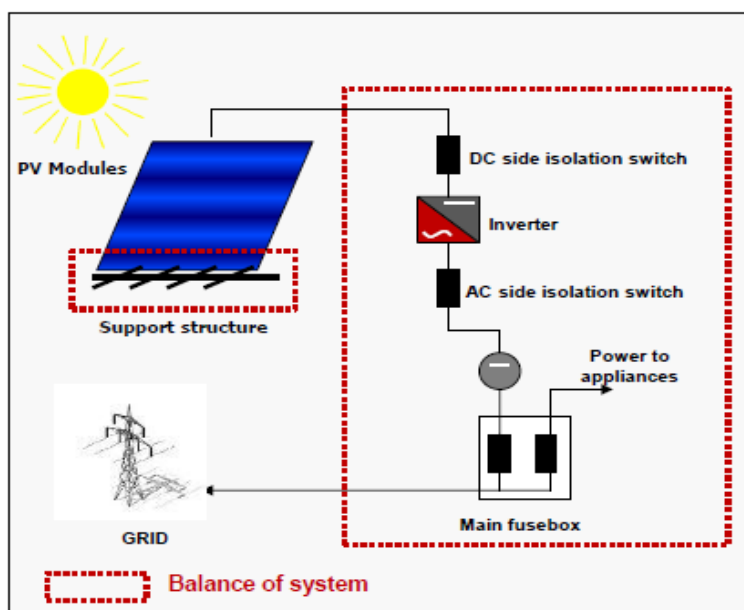


Figure 5. Diagram of a grid-tied solar energy system

Source: https://energypedia.info/images/4/41/SBC_Energy_Institute_Solar_PV_FactBook.pdf

7. 1 Photovoltaic solar modules

The performance of the solar module is influenced by several factors: its dimensions (installed capacity), technological efficiency, site irradiation, surface cleanliness, power electronics (such as the engagement of a Maximum Power Point Tracking device - MPPT), and potentially a tracking system (which is uncommon in rural electrification). Given that sunny circumstances prevail in most poor nations, an installed capacity of 1 kWp (often comprising 4-6 individual modules with a cumulative area of around 8 m²) can produce over kWh yearly. In temperate, overcast climates, the modules may achieve merely 50% or less of this output. The majority of commercially available solar modules can generate electricity for a minimum of twenty years. Panel manufacturers typically provide a warranty of over 90% of rated output for the initial 10 years and over 80% for the subsequent 10 years. High-quality panels are anticipated to operate for a duration of 30 to 35 years.

The maintenance of photovoltaic modules is very straightforward, as the predominant technical issues arise from misaligned or soiled modules, which can be seen visually. In such circumstances, the captured energy diminishes, potentially disrupting the energy balance. Therefore, monitoring the surrounding area is crucial not just to prevent shadowing but also to mitigate the possibility of hot spots that could harm the generator.

Maintenance and sustainable operation are less problematic when market-based methods to photovoltaic systems are implemented, with private entities accountable for the operation of these assets and systems. Nonetheless, community or government-based management remains the prevailing reality in numerous countries. To ensure the continued operation of government/community-managed photovoltaic systems, the availability of a maintenance service provider and funds must be secured.

Solar modules may be effortlessly cleaned with water and a sponge; however, regular maintenance is still essential. This should encompass the inspection of cables and their securement, the access and examination of the junction box, and the strain relief of electrical cables. The user should conduct regular visual inspections of the wires to avert potential damage inflicted by animals. Ultimately, photovoltaic systems situated in coastal areas are susceptible to "blooming" effects on the aluminium frame due to saline air, perhaps resulting in corrosion if not managed appropriately.

7.2 Photovoltaic Cables

Solar cable is the interconnecting cable utilised in photovoltaic power generating. A solar cable connects solar modules and other electrical components within the photovoltaic system. A prevalent characteristic of the majority of solar power systems is their outdoor application, marked by elevated temperatures and intense UV radiation. Single-core cables (2.5/4.0/6.0 up to 35 mm²) are typically utilised, including a maximum allowable DC voltage of 1.8 kV and an operational temperature range of -40°C to +90°C. A three-core AC cable is utilised for grid connection with a single-phase inverter, whereas a five-core cable is employed for three-phase feed-in.

7.3 Mounting mechanisms

Ground-mounted solar power systems comprise solar panels secured by racks or frames affixed to terrestrial mounting supports. Ground-based mounting supports comprise:

- Pole mounts that are either pushed into the ground or embedded in concrete;
- Foundation supports including concrete slabs or poured footings; Ballasted foundation mounts, including concrete or steel bases, utilise weight to stabilise

the solar panel system without necessitating ground penetration. This mounting technique facilitates the decommissioning or relocation of solar panel systems without the need for ground excavation.

Roof-mounted solar power systems comprise solar panels secured by racks or frames affixed to roof-based mounting supports. Roof-mounted supports comprise:

- Pole mounts affixed directly to the roof structure, potentially utilising supplementary rails for the attachment of panel racking or frames;
- Ballasted footing mounts, including concrete or steel bases, utilise weight to stabilise the panel system without necessitating direct penetration. This mounting technique facilitates the decommissioning or relocation of solar panel systems without affecting the roof

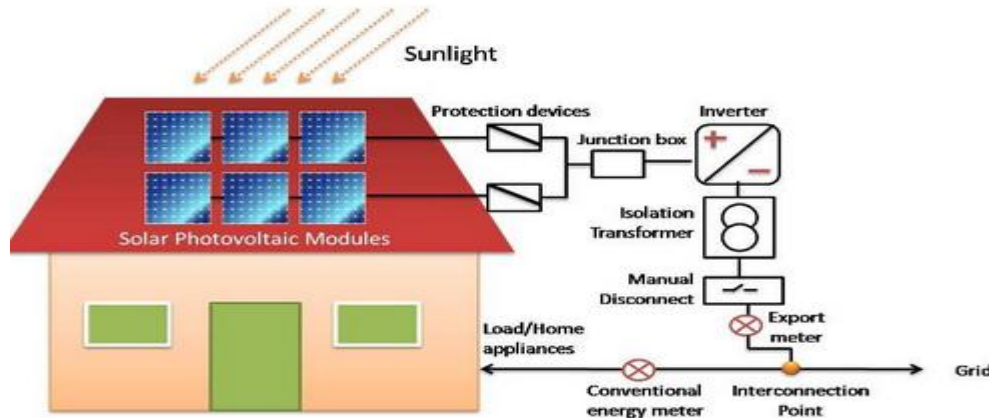


Figure 6. Roof-mounted solar power systems Source: <https://greencleanguide.com/how-grid-interactive-roof-top-solar-pv-systems-work/>

Fixed racks secure panels in a stationary position as the sun traverses the sky. The fixed rack determines the angle at which the panel is positioned. Tilt angles corresponding to the installation's latitude are prevalent. A minimum tilt angle is necessary for rainwater drainage in tropical climates.

Solar trackers enhance the energy output per panel, albeit at the expense of mechanical complexity and maintenance requirements. Single-axis systems follow the sun's trajectory from east to west, enhancing performance by 20 percent or more compared to fixed systems in regions with high insolation. Dual-axis trackers adjust angles along both the x and y axes, often producing approximately 8 to 10 percent more energy than single-axis trackers, contingent upon location.

7.4 Solar Charge Controller

A charge controller is essential for powering DC equipment using solar modules. The charge controller delivers a regulated DC output, stores surplus energy in a battery, and monitors battery voltage to avert undercharging or overcharging. An inverter can be linked to the output of a charge controller to power alternating current (AC) loads. A shunt charge controller or shunt regulator redirects surplus electricity to an auxiliary or "shunt" load, such as an electric water heater, when batteries reach maximum capacity.

7.5 Inverter

Inverters can be categorised into three primary types:

- Stand-alone inverters operate in isolated systems, getting their DC electricity from batteries charged by photovoltaic arrays. Numerous stand-alone inverters additionally feature built-

in battery chargers to recharge the battery from an available AC supply. Typically, devices do not connect to the electric grid and, therefore, are not mandated to possess anti-islanding protection.

- Grid-tie inverters synchronise phase with a utility-provided sine wave. Grid-tie inverters are engineered to immediately deactivate in the event of a power supply interruption, ensuring safety. They do not supply auxiliary power during utility interruptions.

Battery backup inverters are specialised inverters designed to extract electricity from a battery, regulate the battery charge through a charge controller, and transfer surplus energy to the utility grid. These inverters can provide AC power to designated loads during a utility interruption and must include anti-islanding protection.

Single-phase inverters are utilised in low to medium-sized facilities with capacities ranging from 300 Wp to 90 kWp. Multiple inverters are required to attain this amount of power capacity. The outputs of each inverter and the facility's protections are consolidated in a "Main Low Voltage Board." Some installers configure three-phase 400 Vac applications utilising single-phase inverters; this installation necessitates meticulous phase balancing. Cost is the primary factor influencing the selection of single-phase inverters over three-phase inverters. This short-term strategy neglects (i) the additional expenses associated with wiring and monitoring the AC system's balance, (ii) potential ground current through the neutral, among other issues. In the event of an inverter failure or a malfunction in one of the chains connected to the inverters, a phase imbalance arises, resulting in grid disturbances and triggering a security trip for the entire system.

Three-phase inverters are employed in medium to large-scale facilities, with capacities ranging from 5 kWp to several MWp. Various configurations of inverters are available to attain this power capacity, specifically designed for systems from 10 kWp to 1 Megawatt. Outputs and protections are centralised at the primary low voltage board when connected to the grid at low voltage. A transformer is necessary for connection to the medium voltage grid. For installations exceeding 100 kWp and reaching several megawatts, such as solar power plants, a central inverter will be employed to feed current straight into a medium voltage transformer.

7.6 Power sources

The *Lead Acid battery* consists of plates, lead, and lead oxide, along with various elements that modify density, hardness, and porosity. It contains a solution of 35% sulphuric acid and 65% water, referred to as the electrolyte, which facilitates a chemical reaction that generates electrons. During discharge, sulphur accumulates on the battery plates, and upon recharging, the sulphur reverts to the electrolyte.

Battery Maintenance: The lead battery must be cleansed with a solution of baking soda and water. Cable connections should be cleaned and secured, as battery issues frequently arise from unclean and loose connections.

Battery warranties are typically prorated based on the elapsed months relative to the warranty duration. Merely 30% of batteries sold currently attain the 48-month lifespan. Furthermore, 80% of battery failures are attributed to sulphate accumulation, which transpires when sulphur molecules in the electrolyte (battery acid) become excessively discharged, leading to a coating on the battery's lead plates.

Nickel-metal hydride battery (NiMH): This type has become prevalent in both consumer and industrial applications. It utilises a hydrogen-absorbing alloy for the negative electrode in lieu of cadmium. Following the prohibition of cadmium due to its toxicity, NiMH batteries have entirely replaced nickel-cadmium (NiCd) batteries.

Lithium-ion battery technology is employed in electric and hybrid vehicles, experiencing increased production capacity and declining costs (e.g., 3000 Euros for 10 kWh with a 10-year warranty). These batteries exhibit an excellent energy-to-mass ratio and a minimal charge retention loss during periods of inactivity. *Lithium-ion polymer batteries* are lightweight and may be manufactured in various shapes.

Table 1. Characteristics of various types of batteries

Type	Volta	Energy density			Power	Eff.	discha	Cycles	Lif
	V	MJ/kg	Wh/k	Wh/l	W/kg	%	%/mo	#	yea
Lead-	2.1	0.11-	30-40	60-	180	70-92	3-4	500-	20
NiMH	1.2	0.11-	30-80	140-	250-	66	30	500-	
Li ion	3.6	0.58	150-	250-	1800	80-	5-10	1200	10
Li-	3.7	0.47-	130-	300	3000+	99.8%	2.8-	500-	2-

8. FUNDAMENTAL COMPONENTS OF DESIGN

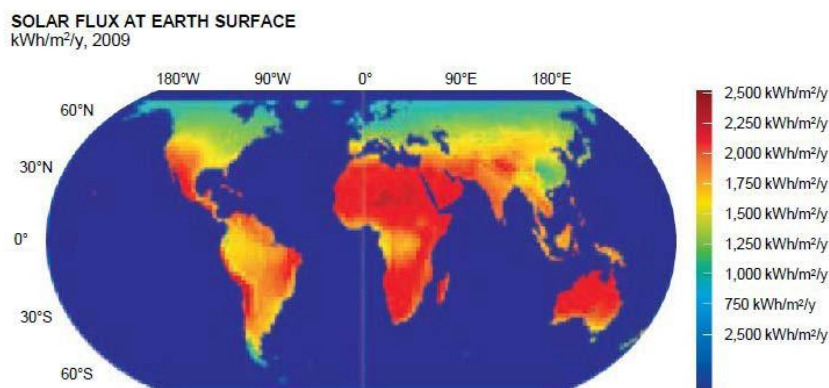
The efficacy of a photovoltaic (PV) plant is contingent upon climatic conditions, the utilised equipment, and the system configuration. The principal energy input is solar irradiance and global irradiation on the plane of the solar modules, which comprises both direct and diffuse radiation. A crucial factor influencing system output is the conversion efficiency of the solar modules, which is particularly dependent on the type of solar cells employed, ranging from 14% to 19% for commercially available crystalline solar cells.

8.1 Solar Irradiance

Solar irradiance refers to the radiation emitted by the sun that passes through Earth's atmosphere. It is quantified by satellites positioned near the outer layer of the atmosphere, known as the solar constant, which measures 1361 W/m². Solar radiation from the sun is diminished by the atmosphere before it reaches the ground, which can be categorised into two primary types: clear and cloudy. Due to scattering and absorption within the atmosphere, the final irradiance value that reaches the ground and can be harnessed by photovoltaic modules is approximately 1000 W/m². This represents the sun's power.

Direct normal irradiation (DNI) refers to the quantity of solar radiation incident per unit area on a surface maintained perpendicular to the direct rays from the sun at its present position in the sky. The cumulative daily solar irradiation per square meter represents the total energy received daily (kWh/m²). Additionally, monthly or annual totals can be quantified or simulated using various programs. The overall power sum over a specified duration equates to total energy, defined as energy *power x time*.

Photovoltaic (PV) modules are systems that convert incoming light into electricity. Africa possesses significant solar energy potential, with most regions receiving over 320 days of bright sunlight annually and experiencing global irradiation levels nearing 2,000 kWh per square meter (kWh/m²), which is double the average in Germany. The optimal solar resources are concentrated in the Sahara, North Africa, and certain areas of Southern Africa, where irradiation levels approach 2,500 kWh/m². Central and West Africa generally have lower irradiance levels, particularly near the Gulf of Guinea.



Source: Breyer and Schmidt (2010); IEA (2011), "Solar Energy Perspectives"
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Figure 7. Solar Flux at earth surface.

Source: https://energypedia.info/images/4/41/SBC_Energy_Institute_Solar_PV_FactBook.pdf

8.2 Conversion Efficiency – Loss Diagram

Various factors, including light absorption losses, mismatch, cable voltage drop, conversion efficiencies, temperature effects, and other parasitic losses, contribute to the discrepancies between Direct Normal Irradiance (DNI) and the actual AC power supplied to the grid. The loss diagram offers a concise overview of the quality of a photovoltaic (PV) system design by pinpointing the primary sources of losses, as depicted in the diagram below.

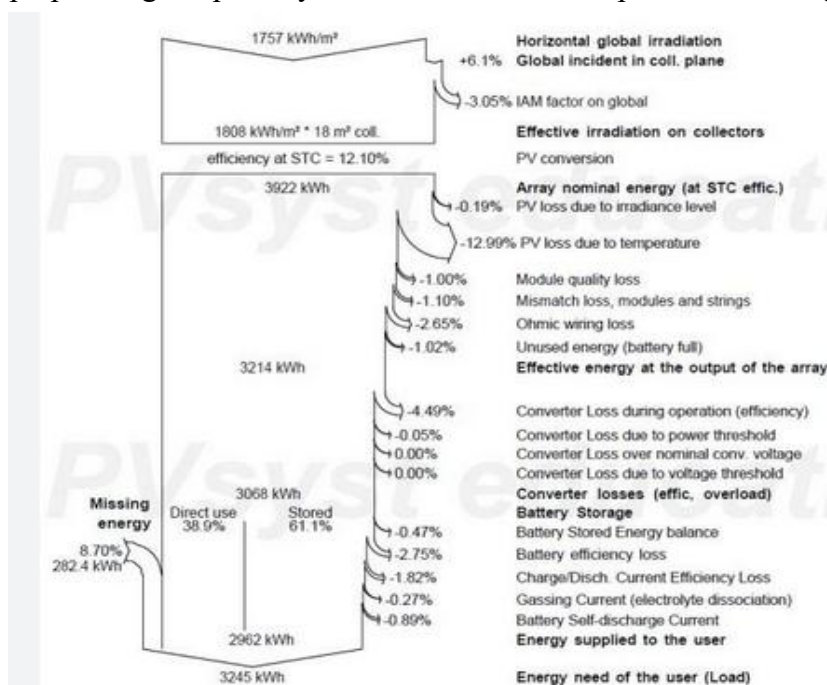


Figure 8. loss diagram of solar PV system Fig.12 represents the loss diagram of solar PV system.

Source:

https://www.researchgate.net/publication/341238063_Design_and_Performance_evaluation_of_Proposed_2_kW_Solar_PV_Rooftop_on_Grid_System_in_Odisha_using_PVsyst/figures?lo=1

8.3 Loss diagram generated using PV-SYST software

Each loss is characterised as a percentage of the preceding energy quantity. Consequently, the percentage values are not additive; when aggregating the losses, the total percentage does not equal the sum of the individual values.

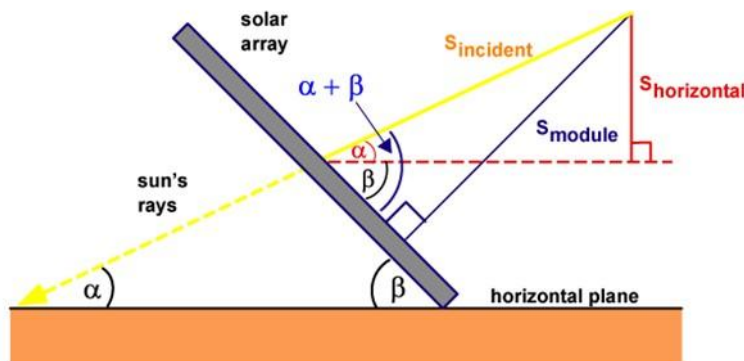


Figure 9. Global incidence on the collector plane.

Source: <http://www.pveducation.org/pvcdrom/properties-of-sunlight/solar-radiation-on-tilted-surface>

The global incidence on the collector plane results from the transposition of irradiance from horizontal ("S horizontal" as indicated in the solar irradiance atlas) to the plane of the array ("S module" at an angle β relative to the horizontal).

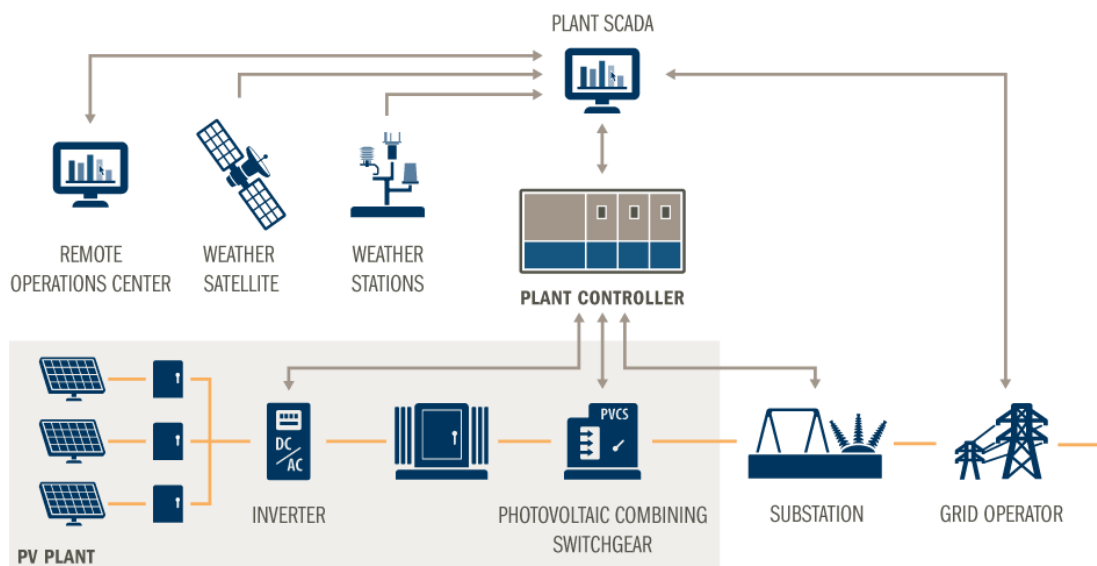


Figure 10. Technologies and capabilities/grid integration for Solar Systems

Source: <http://www.firstsolar.com/en/technologies-and-capabilities/grid-integration>

The incidence effect (or IAM, for "Incidence Angle Modifier") refers to the reduction of irradiance that actually reaches the surface of the photovoltaic cells beneath the protective layer (typically glass with an antireflective coating) compared to irradiance at normal incidence, attributable to increased reflections at higher incidence angles.

The Air Mass represents the distance light travels through the atmosphere, normalised to the minimum distance (when the sun is directly overhead). It quantifies the attenuation of light intensity as it traverses the atmosphere, being absorbed by air and particulate matter. The Air Mass is defined as:

$$AM = 1/\cos(\theta)$$

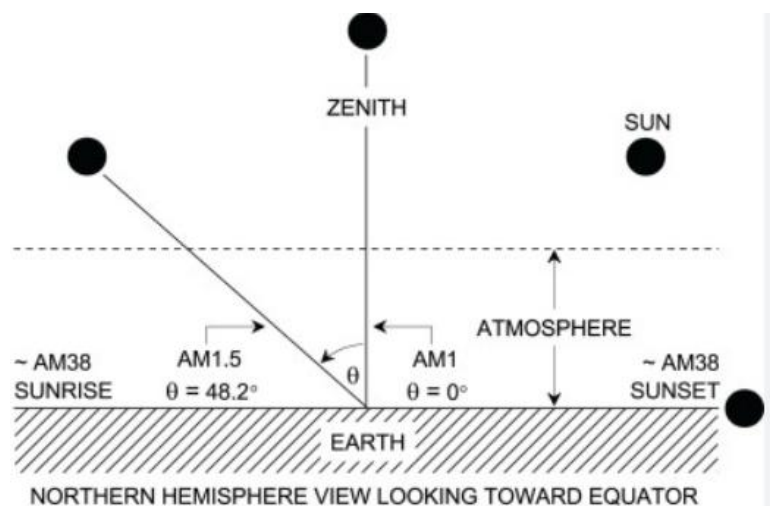


Figure 11. Solar geometry: Angle of Incidence (AOI), Zenith Angle (z), and air mass (SO:ZO).
 Source: <https://www.sciencedirect.com/topics/engineering/air-mass>

Here, θ denotes the angle from the vertical (zenith angle). When the sun is positioned directly overhead, the Air Mass equals 1. Source: <http://www.pveducation.org/pvcdrom/properties-of-sunlight/air-mass>.

8.4 Photovoltaic cell conversion efficiency

A crucial factor influencing the system's output is the conversion efficiency of the solar modules, which is particularly contingent upon the type of solar cells employed. Upon commissioning, the normalised solar cell efficiencies at Nominal Operating Cell Temperature (NOCT) of 46°C are as follows:

- Monocrystalline or Polycrystalline silicon cells 12.5%-15%
- Thin film cells: 9.5% - 10%
- Multi-junction cells: 33%-35%

8.5 Photovoltaic conversion loss attributable to temperature

The normal test circumstances stipulate a cell temperature of 25°C; nevertheless, modules typically operate at significantly elevated temperatures. For crystalline silicon solar modules exclusively, the direct current power output diminishes by 0.7-0.9% for each degree Celsius over 25°C.

8.6 Photovoltaic conversion loss attributable to module mismatch

The total power output of the photovoltaic array is consistently inferior to the aggregate maximum output of the individual modules. This phenomenon arises primarily because, within a series of modules (or cells), the lowest current dictates the current of the entire series. This discrepancy, termed "Mismatch loss," results from minor variations (statistical distribution of cell parameters) in performance among modules and leads to a minimum power loss of 2% in the system.

8.7 Photovoltaic conversion loss attributable to wire resistance

Power is also dissipated due to resistance in the system wiring. These losses should be minimised, however maintaining them below 1% is challenging. A pragmatic reduction factor for these losses is 99% or negative 1%.

8.8 Photovoltaic conversion loss attributable to the inverter

The direct current generated by the solar module must be converted into alternating current using an inverter, resulting in some power loss during the conversion. Contemporary inverters exhibit peak efficiencies ranging from 96% to 98%, as stated by manufacturers.

8.9 Photovoltaic degradation attributable to module ageing

The median degradation rate is approximately 0.5% per annum, with modules produced post-2000 exhibiting a markedly reduced degradation rate, resulting in a mere 12% loss of output performance over 25 years. Conversely, a system utilising modules that degrade at 4% per annum will experience a 64% reduction in output during the same timeframe. Numerous panel manufacturers provide a performance guarantee, generally ensuring 90% output after ten years and 80% after 25 years. The output of all panels is typically guaranteed within a tolerance of plus or minus 3% during the initial year of operation.

8.10 Performance Ratio (PR)

The performance ratio (PR) measures the losses between the nominal DC output of solar modules under standardised test conditions and the actual AC power supplied to the grid. This encompasses various factors, including light absorption losses, mismatch, cabling, and inverter efficiency. In contemporary solar installations, the performance ratio is generally expected to be around 80%.

8.11 Utility-Scale Photovoltaic Systems



Figure 12. Utility-Scale Photovoltaic Systems Source: energy.mit.edu/news/solar-photovoltaics-the-benefits-outweigh-the-costs/

A substantial photovoltaic power facility comprises:

- Photovoltaic array composed of discrete modules
- Direct Current (DC) bus

- Direct Current to Alternating Current power inverters
- Alternating current voltage electrical systems
- Communication and botanical surveillance system

Photovoltaic modules are affixed to support structures and interconnected to provide power output to the electronic power conditioning subsystem. Solar modules generate direct current (DC) electricity; therefore, solar power plants require conversion equipment to transform this into alternating current (AC), the form of electricity transmitted by the grid. This conversion is accomplished by grid-connected inverters, which are engineered to automatically shut down in the event of a power supply interruption for safety purposes.

The efficacy of a photovoltaic plant is contingent upon climatic circumstances, utilised equipment, and system architecture. The principal energy input is the global sun irradiance incident on the solar panels, which comprises both direct and diffuse radiation components.

The advancement of large-scale utility photovoltaic (PV) systems is associated with the policies and regulations governing the electricity sector, particularly concerning renewable energy generation, both centralised and decentralised. The Feed-in Tariff policy has been implemented by several nations. A Power Purchase Agreement (PPA) is invariably required for all large-scale PV installations.

In large-scale photovoltaic power plants, it is essential to assess grid stability and the reliability of power flows during a grid connection study. The power plant may complicate voltage regulation along the feeders. Sophisticated power electronics can enable the power plant to actively participate in voltage regulation. Additionally, the power plant may interfere with system protection schemes, complicating fault detection and coordination of protective devices. Innovative sensors, communication technologies, and management systems will facilitate the restoration of system reliability.

8.12 Rooftop Solar Photovoltaics

A rooftop photovoltaic power station, or rooftop PV system, is a solar energy system with electricity-generating modules installed on the roofs of residential or commercial structures. Its components comprise photovoltaic modules, mounting systems, cables, solar inverters, and various electrical accessories. These rooftop systems are smaller than ground-mounted photovoltaic power stations, which operate in the megawatt range. Typically, rooftop PV systems on residential buildings have capacities of approximately 5 to 20 kilowatts (kW), whereas those on commercial buildings can exceed 100 kilowatts.

The advancement of rooftop photovoltaic systems is associated with net metering policies and regulations. Net metering permits grid-connected electricity consumers who generate their own power to "bank" or "store" excess electricity during periods of overproduction (such as solar energy during peak daylight hours) and to offset their grid consumption with this stored electricity at other times (for instance, during nighttime,

morning, and evening hours). Net metering is typically, though not exclusively, applied to small-scale generators utilising renewable energy sources.

9. STANDARD BENCHMARKS

9.1 Cost Trends of Photovoltaic Systems

The expense of a photovoltaic (PV) system is contingent upon its market, although patterns are globally applicable. For instance, the overall cost of a PV system in Germany diminished from \$5.43/Wp in 2009 to \$2.40/Wp in 2015, indicating a reduction of around 60% over six years.

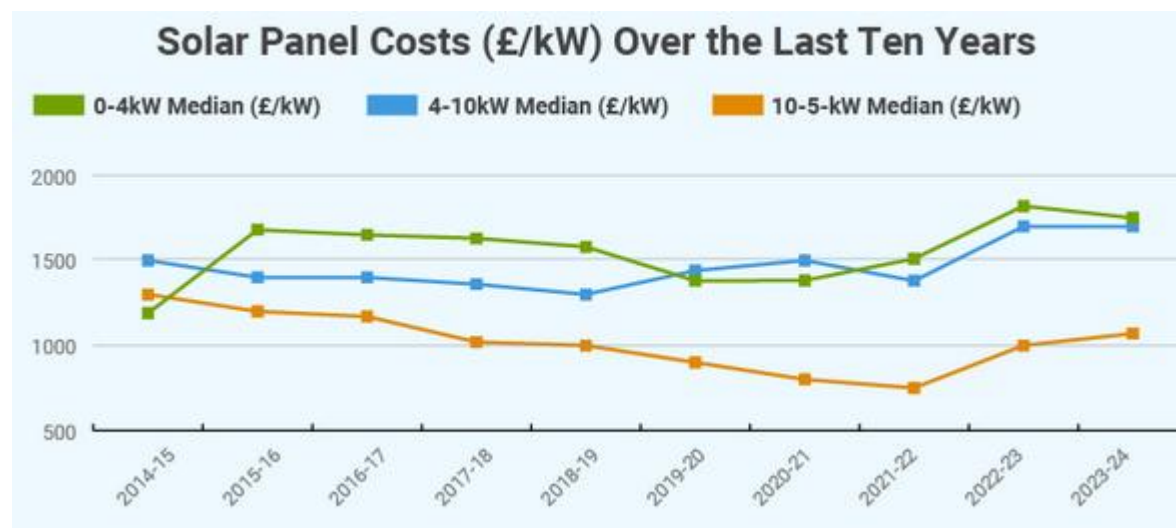


Figure 13. Cost of Solar Panels Source: <https://www.greenmatch.co.uk/blog/decrease-in-solar-costs>

- Over the past decade, the cost of solar panels has decreased globally by 90%, now being under \$0.20 (£0.15) per watt.
- Conversion efficiency improved from 1–2% to 22% within the past century, reducing manufacturing and installation costs.
- Incentives like the Feed-in Tariff and Smart Export Guarantee have driven adoption and cost reduction.
- Prices are expected to drop to \$0.097 (£0.075) per watt by 2030, further accelerating adoption.

Solar panels, once an expensive product, are now the cheapest they have ever been, with prices declining every year worldwide. This dramatic decline is a huge win for sustainability. As solar panel costs become more accessible, homeowners and businesses are now able to implement greener energy solutions. This shift helps reduce carbon emissions and promotes a more sustainable future.

In the last decade, solar panel costs have fallen by **90% worldwide**, according to [Our World Data](https://ourworldindata.org/data-insights/solar-panel-prices-have-fallen-by-around-20-every-time-global-capacity-doubled). (<https://ourworldindata.org/data-insights/solar-panel-prices-have-fallen-by-around-20-every-time-global-capacity-doubled>)

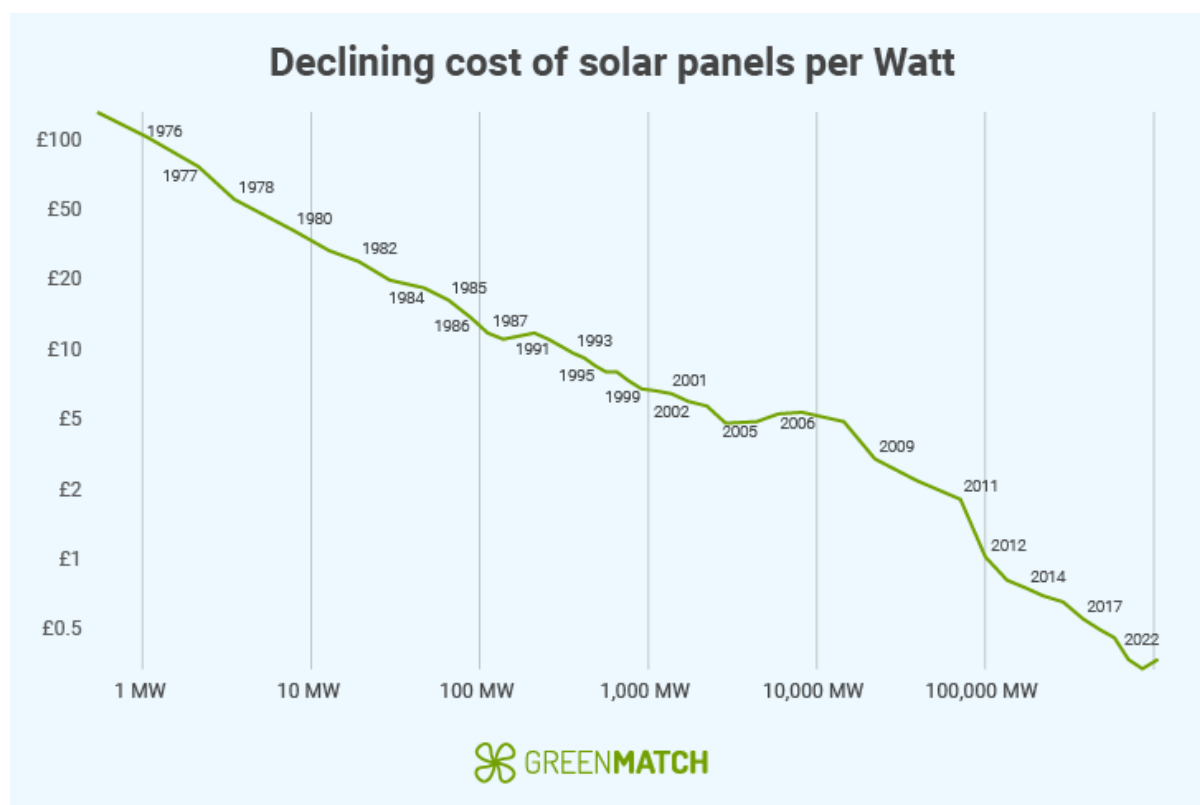


Figure 14. Declining cost of Solar panels:

Source: <https://www.greenmatch.co.uk/blog/decrease-in-solar-costs>

To accelerate sustainable practices and encourage more people and governments to adopt solar energy, it is important to forecast the future costs of solar panels. Forecasting future costs relies on looking at its decline and the factors that contribute to it. In this article, we delve into the breakdown of the cost evolution of solar panels, the reasons for their decline, and the future outlook of solar panel prices.

9.2 Economic and ecological dimensions

9.2.1 Financial considerations

Solar photovoltaic plants are capital-intensive infrastructures characterised by low operation and maintenance expenses in the absence of batteries. The comprehensive cost distribution is as follows:

- Capital expenditure consisting of:
 - Supply and installation of photovoltaic modules and support structures.
 - Supply and installation of inverter equipment.
 - Battery banks (optional).
 - Generator set (optional),
 - Supply and installation of electrical instruments and controls (I&C).
 - Project indirect expenses, charges, and contingency provisions, and Owner's expenses (excluding project finance expenses).
- Operational and Maintenance expenses (O&M) encompassing:
 - Fixed O&M expenses, which do not fluctuate greatly with generation, indicate that operating labour costs are often minimal, as plants are automated and maintain a

- limited number of staff on-site during standard operations.
- Variable O&M costs are production-related expenses that fluctuate with electrical generation.
- Significant maintenance expenses (The repair and replacement of massive electro-mechanical equipment necessitate qualified personnel and the importation of specialised equipment and spare parts that are frequently unavailable in the African market.)

The subsequent table delineates the standard allocation of capital expenditures for the principal components of a large-scale Solar PV facility. The predominant portion of the cost is ascribed to the PV modules, highlighting the significant sensitivity associated with this expense.

Table 2. Capital expenditures for the 5 MW solar power plant.

Category	Amount
Land plot acquisition	EUR 250,000
Grid connection fee	EUR 190,000
Main project design	EUR 50,000
Groundworks	EUR 210,000
Concrete works	EUR 170,000
Metal substructure with installation	EUR 375,000
Solar modules and inverters with installation	EUR 1,650,000
Substation with construction works	EUR 350,000
Electric and other cables	EUR 280,000
Supervision works	EUR 60,000
Other construction works	EUR 180,000
Overheads (10%)	EUR 376,500
Total	EUR 4,141,500
Total per kW	EUR 828.30

The primary benefit of solar photovoltaic technology is the substantial reduction of variable costs, particularly fuel expenses. Due to the standardised design and mass production of solar modules, their manufacturing costs can be maintained at acceptable levels.

Most commercially available solar modules are engineered to produce electricity for a minimum of twenty years. Manufacturers typically provide a quality guarantee of over 90% of rated output for the initial 10 years and over 80% for the subsequent 10 years. Nevertheless, under moderate climate conditions, modules may be anticipated to have a lifespan of up to 30 years.

The energy payback time (EPBT) for photovoltaic (PV) modules refers to the duration required to generate the total energy consumed throughout their life cycles. Presently, the EPBT ranges from six months to two years, contingent upon location, solar irradiation, and technology. Solar PV systems emit minimal greenhouse gases during operation. Moreover, a solar photovoltaic power plant will supplant fossil fuels utilised in traditional power generation, either diminishing import reliance or freeing fossil resources for alternative applications. Under climate change regulations, the abatement effect on greenhouse gas emissions can be monetised through carbon credits, so generating additional revenue.

Solar photovoltaic power is typically regarded as a "must-run" energy source. A solar photovoltaic plant lacks energy storage capacity and hence cannot synchronise power producing output with consumer demand. Solar photovoltaic power is frequently seen as a "non-firm" energy source. It is unfeasible to guarantee a consistent power generation output for an extended duration. The power purchase agreement (PPA) stipulates that generation may be below expectations for a specified duration, providing the plant can thereafter compensate for the generation shortfall. This represents a conventional "non-firm" agreement, which is the normal arrangement for solar photovoltaic generating facilities. Solar photovoltaic plants typically produce greater energy output in the dry season compared to the wet season. The solar radiation pattern and corresponding electricity generation are somewhat predictable in the short term (day-ahead scheduling).

9.2.2 Ecological consequences

Upon the completion of a photovoltaic (PV) facility, the project generates no direct waste and exhibits significantly lower carbon dioxide (CO₂) emissions compared to fossil fuel power plants. The sole carbon footprint arises from the manufacturing of equipment and the construction of the plant. The total land area required for ground-mounted systems varies based on technology, site topography, maintenance choices, and geographical location (latitude). Large-scale PV systems necessitate approximately 1.7 to 5 hectares per megawatt (MW). Certain thin-film PV cells, such as Cadmium Telluride (CdTe), contain hazardous materials. Improper handling and disposal of these substances could pose serious environmental or public health risks. Nonetheless, manufacturers possess a substantial financial incentive to ensure the recycling of these valuable and often scarce materials rather than their disposal.

Pico-PV systems, including solar lanterns and solar home systems, frequently utilise batteries containing hazardous materials. Many developing nations lack sufficient battery collection and recycling initiatives. This issue necessitates attention, as it may undermine the advantages provided by these systems. Additionally, large-scale PV installations in arid regions require water for panel cleaning to remove dust.

9.2.3 Societal influence

Solar photovoltaic systems exert a substantial beneficial influence, particularly in rural regions distant from the electrical grid. The provision of electricity enhances the quality of life, and when capacity is adequate for lighting and powering educational institutions, healthcare facilities, and public utilities, social services experience significant enhancement. Solar PV systems bolster energy security, and individual solar installations render users resilient to fluctuations in fuel prices, fuel shortages, power outages, or inflation. For large-scale photovoltaic installations, land management considerations, particularly regarding ownership, must be addressed.

10. ORGANISATIONAL FRAMEWORKS

The various organisational models presently employed globally can be encapsulated in Table 3.

Table 3. Various Solar organisational models presently employed globally

Model	ownership	Control	Operation maintenance	Finance	Utility's role
G0.0	End-user	End-user	End-user	End-	Passive
G1.0	Third-party	End-user	Third-	Third-	Facilitator
G2.1	Third-party or end-user	Third-party or end-user	Third-party	Third-party	Facilitator and passive PV services buyer
G2.2	Third-party or end-user	Utility	Third-party	Third-party	Facilitator and active PV services buyer
G2.3	Utility	Utility	Utility	Utility	System integrator and services seller

11. RESEARCH AND ENQUIRIES

The technical analyses required for the development of a solar power plant project encompass:

- Sun irradiation research: compilation of satellite data, consultation with local meteorological authorities if available, on-site measurement and analysis of sun irradiation, precipitation, wind velocity, and temperature.
- Evaluation of the legal framework: which legal structure is most suitable, and what are the local regulations pertaining to contracts, land ownership, electricity transactions, warranties, etc., as well as the enforcement of contracts.
- Geological assessment: soil characteristics beneath primary civil engineering projects.
- Geographic assessment: topographical survey, site plan with contour lines, project layout incorporating contour lines, evaluation of infrastructural facilities.
- Design of solar photovoltaic systems: arrangement of PV modules, configurations in parallel and series, angle of the photovoltaic array, spacing of the photovoltaic array, and calculation of the efficiency of grid-connected PV systems.
- Power analysis: assessment of power generation and the plant's influence on the current grid system.
- Design of civil infrastructure: powerhouse (plan, section), access roads.
- Design of electrical apparatus and specification data sheet: inverters, electrical control systems and SCADA (Supervisory Control and Data Acquisition), lightning protection and grounding, relay protection and metering, electric single line diagram (including protection and metering), 33 kV switchyard (plan and section), medium voltage (MV) and low voltage (LV) cubicles, generator transformer and protection, station transformer, medium voltage line, metering system, and station auxiliaries.
- Operational instruments: inventory of essential spare components, inventory of tools.

12. Environmental and Social Impact Assessment (ESIA)

Economic analysis: cost estimates (bill of materials and cost data sheet), operational and maintenance expenses, applicable feed-in tariff and anticipated revenue, cost-benefit analysis.
Risk assessment: primary risks and mitigation strategies.

12.1 Duration

The execution (up to the initiation of operations) of a solar PV project is contingent upon its scale. A standard sequence of steps can be broadly outlined in Table 4.

Table 4. Standard sequence of steps for Solar Projects

Step/Phase	Duration range	Main Activities/Method
Identification	1 to 3 months	On site reconnaissance, desk studies, data
Pre-feasibility study	3 to 6 months	On site surveys, preliminary design and
Feasibility study (Including ESIA)	6 to 24 months	On site surveys, in situ tests, economic analysis, cost estimates, design
Detailed design	6 to 12 months	Computations, modeling, bills of quantities
Tender	3 to 6 months	Bidding documents, contracts models
Tendering/Bidding period (till award of)	3 to 6 months	Contractual and administrative documentation package
Mobilization of	9 to 18 months	Commitments of lenders and financing
Implementation	6 to 18 months	Construction, commissioning

The durations presented in the aforementioned table are merely indicative. Generally, for a completely new project, the timeline from identification to commissioning may range from 2 years to over 5 years in adverse scenarios where phases are not completed promptly, contingent upon the project's size and complexity.

12.2 Essential enquiries

Market assessment

- Is there a national policy objective for the proportion of solar energy in the electricity mix and the corresponding strategy? Is it being executed?
- Does the policy promote the hybridisation of diesel generators for isolated grids?

Project advancement

- Is the project developer dependable? (Adequate technical proficiency in photovoltaic farms, financial stability, experience in the country of operation, access to funding)?
- Will the national regulations pertaining to this investment type be enforced?

Fiscal examination

- Is the feed-in tariff satisfactory for both parties (project developer and national utility) regarding price, duration, and terms (take or pay on committed energy production, pay per committed available capacity)?
- Is there a reduced tariff for the seller's delivery that falls below the short-term commitment (under generation) and for the buyer's acceptance that is less than the deemed generated energy (under acceptance)?
- Is the maintenance component of the tariff adjusted to labour and photovoltaic equipment costs?
- What effect would the feed-in tariff have on the financial status of the national utility and the electricity costs for end consumers?
- What is the national grid's capacity to accommodate the additional electricity generated?
- Is the photovoltaic project the most cost-effective choice for electricity generation?
- What will be the operational expenses of the photovoltaic power plant, including maintenance costs?

Economic assessment

- What is the project's effect on economic activities and income generation?
- What is the anticipated societal impact on the beneficiary population on education and

health?

- What effect will this photovoltaic power facility have on state finances?
- What are the potential uses for the electrical surplus (market sales, utilisation in industrial processes such as desalination, etc.)?

Organisations and business frameworks

- Is the selected business model suitable for the country?

Technology

- What will be the effect of the new photovoltaic power plant on the grid?
- What actions would be implemented to ensure grid stability regarding voltage and frequency?
- Does it align with essential technological benchmarks? (Anticipated production per kWp installed)?
- Is the land necessary for the construction of the plant accessible, and what will be the implications for the environment and agricultural outputs?
- What measures would be used to guarantee after-sales servicing and maintenance?
- Is sufficient water accessible on the location for cleaning the PV modules?
Is the chosen location adequately illuminated without any shade?

13. CONCLUSION

Solar photovoltaic technology represents a transformative and increasingly viable solution for addressing Africa's persistent electricity challenges. With abundant solar resources, declining PV system costs, and expanding technological options, African countries can accelerate energy access, support economic development, and reduce greenhouse gas emissions through strategic PV deployment. The literature shows that PV system performance depends not only on solar irradiance but also on appropriate design, choice of technology, and quality of system components. Utility-scale and rooftop PV systems present complementary pathways to expanding solar generation, supported by strong policy frameworks such as FiTs and net metering.

However, achieving sustainable PV integration requires addressing environmental considerations, ensuring battery recycling, conducting robust feasibility studies, and strengthening institutional capacity. As Africa navigates its energy transition, comprehensive planning and adherence to international technical standards will be essential. Solar PV offers a reliable, scalable, and low-carbon energy solution capable of driving long-term socio-economic progress.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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LOW-TEMPERATURE APPLICATIONS OF PHASE CHANGE MATERIALS FOR ENERGY STORAGE: A REVIEW

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ABSTRACT

Thermal storage is highly pertinent for systems that utilise solar energy for thermal applications, as well as for energy conservation in buildings. Phase change materials (PCMs) provide as a compelling alternative for thermal energy storage. This study offers a thorough overview of recent studies on the integration of phase change materials (PCMs) in low-temperature applications, including building envelopes, passive systems in buildings, solar collectors, solar photovoltaic systems, and solar desalination systems. Furthermore, methods for enhancing heat transmission in phase change material systems are delineated. All application studies demonstrate that performance enhances when a PCM is implemented. Combined photovoltaic-thermal systems (PVT) are among the most enhanced technologies. The latent heat storage in a Phase Change Material (PCM) is highly appealing due to its elevated storage density and less temperature fluctuation. The selection of the phase change material (PCM) is crucial for the construction of a latent heat storage system, alongside the heat transmission mechanism within the PCM. The literature contains extensive information on latent heat storage materials and systems. This paper aims to compile knowledge from prior research on phase change materials and latent heat storage systems.

1. INTRODUCTION

Thermal energy storage (TES) refers to the temporary retention of thermal energy at elevated or reduced temperatures. Energy storage mitigates the temporal or quantitative discrepancies between energy supply and demand, significantly contributing to energy conservation. This technique stores thermal energy by heating or cooling a medium, allowing the stored energy to be utilised later for heating, cooling, and power production applications.

Thermal energy storage systems may be classified as either centralised or dispersed systems. Centralised applications may be utilised in district heating or cooling systems, extensive industrial facilities, combined heat and power plants, or renewable energy plants. Distributed systems are mostly utilised in residential or commercial structures to harness solar energy for water and space heating or cooling. In both instances, TES systems may diminish energy use at peak periods. The economic performance of a TES system is significantly influenced by its particular application and

operational requirements, including the quantity and frequency of storage cycles. Generally, PCM and TCS systems are costlier than sensible heat systems and are economically feasible solely for applications requiring a high frequency of cycles. In wealthy nations, a significant limitation for TES implementation is the low rate of new building construction, but in emerging economies, TES systems provide greater deployment potential. TES systems are utilised specifically in edifices and industrial operations. In these applications, over fifty percent of the energy utilised is in the form of thermal energy, the demand for which may fluctuate during the day and from one day to another. Consequently, TES devices can assist in equilibrating energy demand and supply on a daily, weekly, and even seasonal scale. They can diminish peak demand, energy consumption, CO₂ emissions, and expenses, while enhancing the overall efficiency of energy systems. Moreover, the conversion and storage of variable renewable energy as thermal energy can enhance the proportion of renewable energy in the energy portfolio. Thermal Energy Storage (TES) is increasingly vital for electricity storage in conjunction with concentrating solar power plants, allowing solar heat to be retained for electricity generation during periods of insufficient sunlight.

Energy storage mitigates the disparity between supply and demand, enhances the performance and stability of energy systems, and is crucial for energy conservation (Garg et al., 1985; Project Report; n.d). It results in the conservation of premium fuels and enhances cost-effectiveness by minimising energy waste and capital expenditure. For instance, storage would enhance the operation of a power producing facility through load levelling, while increased efficiency would result in energy conservation and reduced generation costs. A promising method for thermal energy storage is the utilisation of phase change materials (PCMs). Regrettably, before the extensive practical use of this technology, it is essential to address certain issues during the research and development phase. The following are types of energy storage methods.

If mass-specific heat capacity is not minimal, denser materials possess smaller volumes and hence offer a greater energy capacity per unit volume. The available space is constrained in both transportation and habitat purposes. The volume used by current storage systems is substantial and may significantly restrict the size of available storage. The quantity of energy storage available is determined by the expense. The expense of floor area or volumetric capacity should be a key factor in optimising storage dimensions.

The technology of thermal energy storage has advanced to a level where it can substantially impact contemporary living. The primary nontechnical application of thermal storage was to provide a consistent temperature in residences, ensuring warmth during frigid winter evenings. Substantial stones, cast iron blocks, and ceramics were employed to retain heat from an evening fire into the night. The industrial revolution heralded the introduction of thermal energy storage as a by-product of energy generation. A range of novel thermal energy storage systems has emerged in the past. A primary application for thermal storage now resides in residential homes. Heat storage at power plants is generally in the form of steam or hot water and is normally for a brief duration.

Recently, additional materials, such as oils with elevated boiling points, have been proposed as heat storage mediums for electric utilities. Alternative materials with elevated heat of fusion at high temperatures have also been proposed for this application. Another application of thermal energy storage in electric utilities is the provision of hot water. The most promising application of thermal energy storage is in solar-heated structures, and virtually any material can be utilised for this purpose.

There are three types of Thermal Energy Storage (TES) systems: 1) sensible heat storage, which involves the retention of thermal energy through the heating or cooling of a liquid or solid medium (e.g., water, sand, molten salts, rocks); 2) thermochemical storage (TCS), which employs chemical reactions to store and release thermal energy. 3) Latent heat storage utilising phase change materials (PCMs), such as the transition from solid to liquid form.

Table 1. A standard comparison of thermal energy storage systems ((Hauer. 2011))

TES	Capacity	Power	Efficiency	Storage period	Cost
System	(kWh/t)	MW)	(%)	(h, d, m)	(€/kWh)
Sensible (hot water)	10--50	0.001-10	50-90	d/m	0.1-10
PCM	50-150	0.001-1	75-90	h/m	10--50
Chemical reactions	120-250	0.01-1	75-100	h/d	8-100

2. Sensible Heat Storage

Heating a liquid or solid without altering its phase is referred to as sensible heat storage. Sensible heat storage is comparatively economical in relation to PCM and TCS systems and is suitable for residential systems, district heating, and industrial applications. Nevertheless, sensible heat storage typically necessitates substantial volumes due to its poor energy density, which is three to five times inferior than that of phase change materials (PCM) and thermochemical storage (TCS) systems, respectively. Moreover, sensible heat storage devices necessitate meticulous design to release thermal energy at uniform temperatures. A number of developers in Germany, Slovenia, Japan, Russia, and the Netherlands are engaged in the advancement of new materials and methodologies for all Thermal Energy Storage (TES) systems, encompassing their incorporation into building walls (for instance, by embedding phase change materials within plaster or air vents) and the conveyance of thermal energy across various locations. The commercialisation of these novel applications is already underway, necessitating verification of their cost, performance, and dependability.

The selection of the material is primarily contingent upon the application's temperature, with water utilised for temperatures below 100°C and refractory bricks employed for temperatures approximately 1000°C. Sensible heat storage systems have a simpler design compared to latent heat or bond storage systems. However, they are disadvantaged by their larger bulk. Consequently, a crucial consideration in the selection of a material for sensible heat storage is its density and specific heat capacity. A secondary drawback of sensible heat systems is their inability to store or supply energy at a uniform temperature.

2.1 Liquids as a Medium for Thermal Storage

A diverse array of chemicals has been utilised in these systems. This encompasses liquids such as water, heat transfer oils, and specific inorganic molten salts, as well as solids like rocks, pebbles, and refractory materials.

Due to its superior specific heat capacity, water is the predominant medium utilised in sensible heat storage systems. Most solar water heating and space heating systems utilise hot water storage tanks situated either indoors, outside, or underground. The tank sizes range from few hundred litres to several thousand cubic meters. A general guideline for determining size is to allocate around 75 to 100 litres of storage for each square metre of collector surface.

Water storage tanks are constructed from various materials, including steel, concrete, and fibreglass. The tanks are adequately insulated with glass wool, mineral wool, or polyurethane. The insulating thickness is substantial, ranging from 10 to 20 cm. Consequently, the expense of insulation constitutes a substantial portion of the overall cost, necessitating the exploration of methods to mitigate this expenditure. Shelton has demonstrated that the insulating properties of the earth encasing an underground tank may be sufficient, perhaps supplying the majority of the necessary insulation thickness. It may require up to one year for the soil surrounding a big storage tank to attain a stable state by heating and drying, necessitating a significant amount of energy for this process. At atmospheric pressure, the temperature of water is restricted to 100°C. Water can be

stored at temperatures slightly over 100°C with pressurised tanks. This has occurred in several occasions.

Table 2. Characteristics of Liquid Media for Sensible Heat Storage.

Medium	Fluid Type	Temp. Range (°C)	Density Kg/m ³	Heat Capacity (J/kg.K)	Thermal Conductivity (W/m.K)
Water	-	0 to 100	1000	4190	0.63 at 38°C
Water-Ethylene Glycol 50/50	-	-	1050	3470	-
Caloria HT43	Oil	-10 to 315	-	2300	-
Dowtherms	Oil	12 to 260	867	2200	0.112 at 260°C
Therminol 55	Oil	-18 to 315	-	2400	-
Therminol 66	Oil	-9 to 343	750	2100	0.106 at 343
Ethylene Glycol	-	-	1116	2382	0.249 at 20°C
Hitec	Molten salt	141 to 540	1680	1560	0.61
Engine oil	Oil	Up to 160	888	1880	0.145
Draw salt	Molten salt	220 to 540	1733	1550	0.57
Lithium	Liquid salt	180 to 1300	510	4190	38.1
Sodium	Liquid salt	100 to 760	960	1300	67.5
Ethanol	Organic liquid	Up to 78	790	2400	-
Propanol	- do -	Up to 97	800	2500	-
Butanol	- do -	Up to 118	809	2400	-
Isobuthanol	- do -	Up to 100	808	3000	-
Isopentanol	- do -	Up to 148	831	2200	-
Octane	- do -	Up to 126	704	2400	-

Heat transfer oils are utilised in sensible heat storage systems at intermediate temperatures between 100 and 300 °C. Dowtherm and Therminol are among the heat transfer oils utilised for this application. The issue related to heat transfer oils is their propensity to deteriorate over time. The deterioration is most severe when utilised over their prescribed temperature threshold. The utilisation of oils poses safety hazards due to the potential for fire exceeding their flash point. Consequently, it is advisable to utilise them in systems with an inert gas overlay. An additional constraint regarding the utilisation of heat transfer oils is their expense. Consequently, they may be deemed suitable exclusively for compact storage systems. Several molten inorganic salts have been evaluated for elevated temperatures (300°C and higher). One is a eutectic composition of 40 percent NaNO₂, 7 percent NaNO₃, and 53 percent KNO₂ (by weight), marketed under the trade name 'Hitec'. Hitec possesses a melting point of 145°C and is applicable at temperatures up to 425°C.

Above this temperature, breakdown and oxidation commence. Another molten salt under consideration for high-temperature storage is sodium hydroxide, possessing a melting point of 320°C and applicable for temperatures reaching 800°C. Nonetheless, it is quite caustic and poses challenges in containment at elevated temperatures. Water, due to its low cost and abundant availability, can be efficiently utilised for the storage of sensible heat.

The benefits and drawbacks of this storage can be encapsulated as follows:

Benefits:

- a. Water is economical, manageable, non-toxic, non-flammable, and readily accessible.
- b. Water possesses a relatively elevated specific heat and high density.
- c. Heat exchangers can be circumvented when water serves as the heat transfer medium in the collector.
- d. Natural convection currents can be employed when energy for pumping is limited.
- e. The storage tank can be charged and discharged simultaneously.
- f. The regulation and management of a water system are adaptable and versatile.

Drawbacks:

- a. Water may undergo freezing or boiling.
- b. Water has significant corrosive properties.
- c. Operational temperatures are restricted to below 100°C and frequently must be significantly lower than this boiling point.
- d. Water is challenging to stratify.

Chemical additives can address issues related to freezing and corrosion. Water can occasionally maintain economic competitiveness at elevated temperatures, particularly when kept in aquifers, despite the necessity for pressure containment. Organic oils, molten salts, and liquid metals mitigate the issues associated with vapour pressure; however, they present additional constraints regarding handling, containment, cost, storage capacity, and operational temperature range. Despite its utilisation in commercial operations, the longevity and cost constraints of these fluids restrict their employment in areas such as space heating. Oils and molten salts have been employed in solar thermal power systems.

2.2 Prudent energy storage in anhydrous molten salts/nitrates

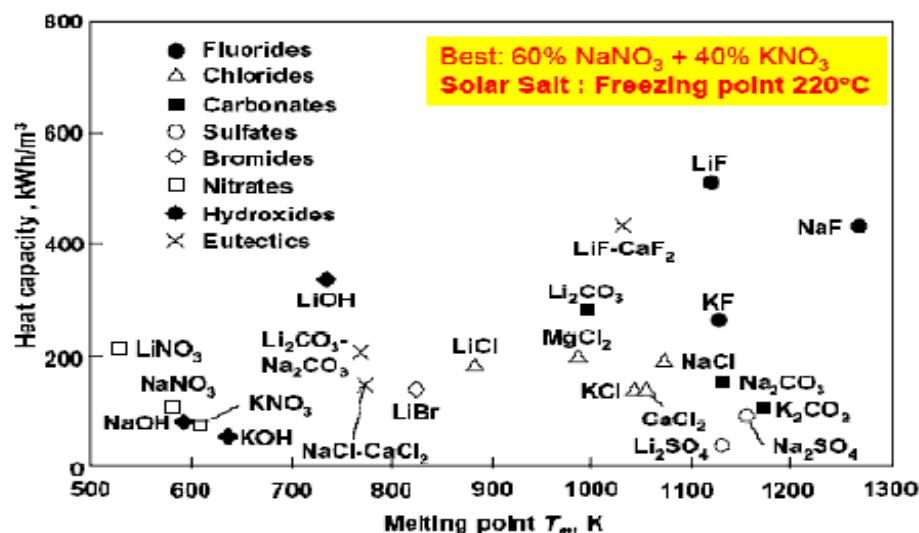
Molten salts are the most appropriate medium for sensible heat storage at extreme temperatures ($T > 100\text{ }^{\circ}\text{C}$). The benefits of molten salts include their elevated thermal stability, comparatively low material expenses, substantial heat capacity, high density, non-flammability, and minimal vapour pressure. Pressurised vessels are unnecessary due to the low vapour pressure.

Molten salts have a higher melting point than organic heat transfer fluids. Consequently, a significant problem associated with molten salts is to prevent solidification during operation. Consequently, auxiliary heating systems or the creation of low-melting-point salts are generally necessary. A novel technique for identifying the composition of salt mixtures with a reduced melting point is introduced at the conclusion of this section. Moreover, the constraints of molten salt storage may stem from the expenses associated with storage media, the potential for corrosion, and the challenges in treating hygroscopic salts.

A non-eutectic molten salt mixture including 60 wt % sodium nitrate (NaNO_3) and 40 wt % potassium nitrate (KNO_3) is employed for sensible heat storage in solar power plants. This combination is commonly referred to as "Solar Salt." The elevated quantity of NaNO_3 relative to the eutectic mixture allows for a reduction in material expenditures. The non-eutectic mixture exhibits a liquidus temperature of approximately 240 °C, whereas its thermal stability limit is around 550 °C. For high-temperature applications, salts containing alternative anions, such as carbonates,

chlorides, and fluorides, may be viable choices. Currently, experience with oxyanion salts and halogen salts is confined to theoretical investigations (Forsberg et al, 2006; Singer et al, 2010). A typical illustration of various types of salts utilised as sensible liquid heat storage materials is presented in the Figure. 1

Figure 1. Molten Salts (Sensible Liquid Heat Storage Materials) (7)



2.3 Additional ways of sensible energy storage are currently under consideration as follows:

2.3.1 Underground Thermal Energy Storage (UTES)

UTES is a prevalent storage technique that use subsurface resources for the storage of both thermal energy and refrigeration. UTES technologies encompass borehole storage, aquifer storage, cavern storage, and pit storage. The selection of these methods is heavily contingent upon local geological circumstances.

2.3.2 Borehole Storage

It relies on vertical heat exchangers situated underground, facilitating the flow of thermal energy to and from subsurface strata (e.g., clay, sand, rock). Numerous initiatives seek to achieve seasonal storage of solar thermal energy during summer for the purpose of heating residential or commercial spaces in winter. Ground heat exchangers are commonly utilised alongside heat pumps, wherein they extract low-temperature heat from the earth.

2.3.3 Aquifer Reservoir

It utilises a natural subterranean aquifer as a storage medium. Thermal energy transfer is accomplished through mass transfer, namely by withdrawing or reinjecting water into the subterranean layer. Most applications include the preservation of winter cold for the purpose of cooling large office buildings and industrial activities throughout the summer. A primary requirement for this technology is the presence of appropriate geological formations.

2.3.4 Cavern and Pit Storage

It relies on extensive subterranean water reservoirs established in the subsoil to function as thermal energy storage systems. These storage alternatives are technically viable; nevertheless, their applicability are constrained due to substantial investment costs. For high-temperature sensible heat storage (i.e., exceeding 100 °C), the preferred approach utilises liquids such as oil or molten salts, the latter suitable for temperatures up to 550 °C. For extremely high temperatures, solid materials like ceramics and concrete are also considered. Nevertheless, the majority of high-

temperature-sensible thermal energy storage alternatives remain in the stages of development or demonstration.

3. LATENT HEAT STORAGE

Latent heat storage (LHS) relies on the absorption or release of heat during the phase transition of a storage medium between solid and liquid or liquid and gas states. Latent heat storage operates on the idea that when heat is applied to a material, it undergoes a phase transition from solid to liquid, storing energy as latent heat of fusion, or from liquid to vapour, storing energy as latent heat of vapourisation. Upon extraction of the stored heat by the load, the material will revert to its solid phase from liquid or to its liquid phase from vapour. The latent heat of phase transition between solid states is minimal. Solid-vapor and liquid-vapor transitions involve significant heat of transformation; yet, substantial volume changes complicate the system and render it impracticable. The solid-liquid transitions entail comparatively little alterations in volume. These materials exhibit a variety of transition temperatures. Sensible heat storage is cost-effective; nonetheless, it is characterised by poor energy density and fluctuating discharge temperatures (energy conversation, n.d).

These challenges can be addressed by phase change materials (PCM)-based thermal energy storage (TES), which facilitates enhanced storage capacities and specific discharge temperatures. The phase transition may occur as either a solid/liquid or a solid/solid event. Melting procedures require energy densities of 100 kWh/m³ (e.g., ice), in contrast to the normal 25 kWh/m³ for sensible heat storage alternatives. Figure 3 juxtaposes the attainable storage capacity at a specific temperature differential for a storage medium with phase transition vs one without.

Phase change materials are applicable for both short-term (daily) and long-term (seasonal) energy storage, employing various processes and materials. The integration of micro-encapsulated phase change materials (e.g., paraffin wax) into gypsum walls or plaster can significantly enhance the thermal mass and capacity of lightweight construction walls. The micro-encapsulated phase change materials (PCMs) harden at night and melt during the day, thereby cooling the walls and minimising or eliminating the necessity for electric chillers. Additional uses for active cooling systems include the utilisation of macro-encapsulated salts that liquefy at a designated temperature. The PCM can be kept in the building's air vent ducts, and cold air can be distributed by extensive ceiling and floor ventilation systems. PCM slurries are a potential technique. Ice slurries or water-paraffin dispersions may be utilised for construction or industrial cooling applications. Slurries, being pumpable, can serve for the storage or distribution of heat energy.

Phase change heat storage offers the benefit of compactness, as the latent heat of fusion for most materials significantly exceeds their enthalpy change for 1 K or even 0 K. The ratio of latent heat to specific heat of water is 80, indicating that the energy necessary to melt one kilogramme of ice is 80 times greater than that needed to increase the temperature of one kilogramme of water by one degree Celsius.

Moreover, the phase change materials (PCMs) solidify and, as a result, are typically unsuitable as heat transfer mediums in solar collectors or for the load. Numerous phase change materials have inadequate thermal conductivity, necessitating extensive heat exchange surfaces. Some are corrosive and necessitate specialised containers. Latent heat storage materials are costlier than the commonly utilised sensible heat storage media, such as water and rocks. These augment the system expenses.

Owing to its substantial expense, latent heat storage is more apt to be utilised when:

- a. High energy density or high volumetric energy capacity is essential, particularly in environments where space is limited or in transportation when both volume and weight must be minimised.

- b. The load necessitates energy at a constant temperature or within a narrow temperature range, or
- c. The storage capacity is limited. Reduced storage possesses a greater surface area to volume ratio, resulting in elevated packing costs. Compactness is crucial for minimising containment expenses. Likewise, heat losses are approximately proportional to the surface area. Compactness is a crucial aspect in minimising heat losses in small-capacity storage systems.

3.1 Classification of Phase Change Materials (PCMs)

Phase Changing Materials can be categorised into three groups based on their composition: 1. Organic PCMs 2. Inorganic PCMs 3. Eutectic PCMs The categorisation of PCM according to their composition (Perez et al, 2010; Microtek Laboratories, 2010) is presented in Table 2.

Table 2. Classification of Phase Change Materials

Pcm Type	Composition
Organic	Paraffin Compounds Compounds Without Paraffin
Inorganic	Hydrated Salts, Metallic
Eutectics	Organic-Organic Organic-Inorganic Inorganic-Inorganic

3.1.1 Organic Phase Change Materials

Organic materials undergo melting and freezing without deterioration or segregation and exhibit self-nucleation properties. Organic phase change materials are categorised into paraffins and non-paraffins.

3.1.1.1 Alkanes

Paraffins consist of mixes of n-alkanes. The heat is emitted during the crystallisation of these alkane chains. As the chain length rises, both the latent heat of fusion and the melting point rise. Paraffins are reliable and economical. Systems utilising them exhibit prolonged freeze and melt cycles. Nonetheless, they exhibit several undesirable characteristics, including limited heat conductivity and flammability. Such unwanted characteristics can be eradicated by adjusting the wax content. Paraffin waxes are the predominant phase change materials (PCMs) utilised in electronic thermal management due to their elevated heat of fusion per unit weight, extensive melting point range, reliable cycling performance, non-corrosive nature, and chemical inertness. In the design of paraffin phase transition materials, void control is crucial due to the volumetric alteration from solid to liquid state. Paraffin phase change materials have low heat conductivity, hence establishing adequate conduction pathways is a crucial design consideration.

3.1.1.2 Non-Paraffins

In contrast to paraffins, each material classified as a non-paraffin has distinct features. They surpass paraffins in quantity. They are abundantly available. The characteristics of these non-paraffins encompass elevated heat of fusion, diminished thermal conductivity, toxicity, and instability at elevated temperatures. Microencapsulation and macroencapsulation of phase change materials are the two methods that categorise them into micro and macro PCMs.

3.1.2 Inorganic Phase Change Materials

Inorganic phase change materials do not experience supercooling to the necessary degrees, and there is no deterioration of latent heat of fusion. Inorganic phase change materials (PCMs) are further categorised into salt hydrates and metallics.

3.1.2.1 Salt Hydrates

The standard formula for salt hydrates is AB_nH_2O . The most notable characteristics of salt hydrates are their high latent heat of fusion, elevated thermal conductivity, and minimal volume fluctuations. They are inert and non-toxic. The primary issue with utilising salt hydrates is congruent melting. The issue of congruent melting can be addressed through mechanical agitation, encapsulation, the

incorporation of thickening agents and water, as well as alterations to the chemical composition of the system. Hydrated salts constitute an additional group. These PCMs possess a substantial heat of fusion per unit weight and volume, exhibit relatively good thermal conductivity for non-metals, and demonstrate minimal volume variations between solid and liquid phases. These materials are infrequently utilised for electronic heat sinks due to their corrosive nature and the unknown long-term dependability over thousands of cycles. The predominant application is for extensive thermal storage systems (e.g., solar heating), where the much reduced cost is highly appealing.

3.1.2.2. Metallic substances

Low melting point metals constitute a subclass of metallic elements. Nonetheless, the application of metals is restricted, even in low-volume scenarios.

3.1.3 Eutectics

A eutectic is a compound of two or more components that has the lowest melting point, wherein each component melts and freezes congruently, resulting in a mixing of the component crystals during crystallisation. Eutectic compositions practically melt and solidify without segregation, as they crystallise into a homogeneous mixture, minimising the potential for component separation. Upon melting, both components liquefy together with improbable separation.

Table 3. PCM Types Include Paraffin Waxes, Non-Paraffin Organics, Hydrated Salts, and Metallics

Property or Characteristic	Paraffin Wax	Non-Paraffin Organics	Hydrated Salts	Metallics
Heat of Fusion	High	High	High	Med.
Thermal Conductivity	Very Low	Low	High	Very High
Melt Temperature (°C)	-20 to 100+	5 to 120+	0 to 100+	150 to 800+
Latent Heat (kJ/kg)	200 to 280	90 to 250	60 to 300	25 to 100
Corrosive	Non-Corrosive	Mildly Corrosive	Corrosive	Varies
Economics	Medium	High to very high	Low cost	Medium to High
Thermal Cycling	Stable	Elevated Temperature Can Cause Decomposition	Unstable over Repeated Cycles	Stable
Weight	Medium	Medium	Light	Heavy

4. THERMAL ENERGY STORAGE THROUGH CHEMICAL REACTIONS

A chemical energy storage system typically consists of one or more chemical molecules. The TES category encompasses sorption and thermochemical processes. In a thermochemical energy system, energy is stored during a dissociation reaction and subsequently retrieved by a chemically reversal reaction (Abedin et al, 2011). In this entirely reversible chemical reaction, the temperature of certain compounds may be increased or decreased. Therefore, this chemical heat energy can be stored using many effective methods for long-term use. The heat retained is contingent upon the quantity of storage material, the endothermic heat of reaction, and the degree of conversion (Atul et al, 2009).

High energy density (i.e., 300 kWh/m³) thermal energy storage systems can be realised by chemical reactions (e.g., thermo-chemical storage, TCS) (energy conversation, n.d). Thermo-chemical reactions, including adsorption (the adherence of a material to the surface of another solid or liquid),

can be utilised for the storage of heat and cold, as well as for humidity regulation. Common applications include the adsorption of water vapour onto silica gel or zeolites, which are micro-porous crystalline aluminosilicates. Open sorption systems utilising lithium chloride for water cooling and zeolites for humidity management are particularly significant for application in hot, humid areas or confined places with elevated humidity levels. Figure 2 illustrates an instance of thermal energy storage via an adsorption process (e.g., water vapour on zeolite): during the charging phase, water molecules are desorbed from the internal surface of the adsorbent. The TES persists in this condition until water molecules are absorbed by the adsorbent, at which point the TES is recharged.

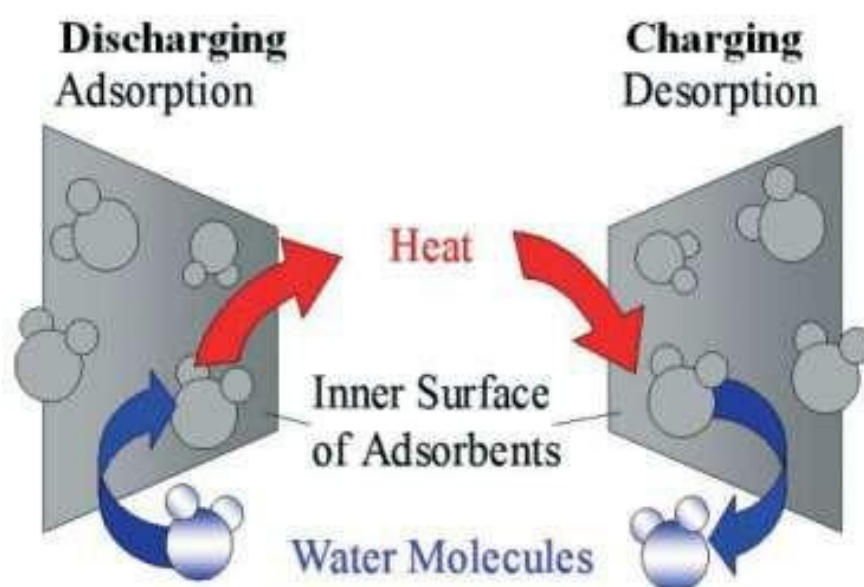


Figure 2 - TES De/Adsorption Mechanism

Thermochemical materials (TCMs) represent a promising alternative for long-term thermal energy storage. The process in question relies on a reversible chemical reaction that is energy-intensive in one direction and energy-releasing in the other way. Typically, TCMs exhibit superior storage density with repeating storage characteristics suitable for sorption storage systems, and certain materials may approach the storage density of biomass features (Hastings et al, 2007). Due to their elevated energy density, thermochemical thermal energy storage systems can offer more compact energy storage compared to latent and sensible thermal energy storage systems (Bales et al, 2006; Hadorn, 2005). Extensive research and trials on diverse storage technologies indicate that thermochemical energy storage systems may emerge as the most efficient and cost-effective means of storing and utilising waste heat (Darkwa et al, 200; Perry et al, 1984).

Table 4. Shows some of the sorption materials that are currently under investigation

Material	Density(ρ), kg/m ³	Energy density, MJ/m ³
Aluminium oxide, Al ₂ O ₃	3970	4320
Barium oxide, BaO	5720	4906
Borax, Na ₂ B ₄ O ₇ ·10H ₂ O	1730	1218
Calcium oxide, CaO	3300	6158
Magnesium oxide, MgO	3580	6874

4.1 Combined Heat and Power Storage Systems

CHPs exemplify systems for the conversion and storage of chemical thermal energy (Kato et al, 2007). A CHP utilises the conversion of thermal energy into potential energy (Wang et al, 2008). CHPs employ reversible chemical reactions and sorption to modify the temperature of thermal energy stored in chemical compounds (Kawasaki, et al, 1999; Wongsuwan et al, 2001). These chemical substances are crucial in the absorption and release of heat (Kato et al, 1996). Depending on the nature of the chemical reaction, numerous chemical substances may be involved in CHPs. A CHP system can be classified as either a mono-variant system or a di-variant system (Wang et al, 2008; Wongsuwan et al, 2001).

5. ECONOMIC ASSESSMENT OF THERMAL ENERGY SYSTEMS

Cost assessments of TES systems encompass storage materials, technical apparatus for charging and discharging, and operational expenses. Thermal energy storage systems for sensible heat are quite economical, as they primarily comprise a basic tank for the storage medium and the apparatus for charging and discharging. Storage medium, such as water, soil, rocks, concrete, or molten salts, are typically cost-effective. The storage material's container need efficient thermal insulation, which could significantly impact the TES cost. Several seasonal thermal energy storage systems have been implemented in Germany (Solites et al, 2007). Most systems have a water reservoir of 5,000-10,000 m³, possessing an energy content of 70-90 kWh/m³ and investment expenditures ranging from €50-200/m³ of water equivalent, resulting in a particular investment cost of €0.5-3.0 per kWh. In UTES systems, boreholes and heat exchangers are the primary cost components for activating subterranean storage. Particular costs vary from €0.1 to €10 per kWh and are significantly influenced by local variables.

Phase change material (PCM) storage and thermo-chemical storage (TCS) systems exhibit considerably more complexity and cost compared to sensible heat storage systems. In numerous instances (e.g., thermo-chemical reactors), advanced heat and mass transport technologies are employed to attain the necessary performance regarding storage capacity and power, resulting in equipment costs significantly exceeding those of the store material. The price of a PCM system typically varies from €10 to €50 per kWh (Solites et al, 2007). The expense of systems employing costly micro-encapsulated phase change materials, which eliminate the necessity for heat exchange surfaces, might be significantly greater. The total cost of complete plasterboard (€17/kg), incorporating micro-encapsulated paraffin for use as a passive cooling mechanism in building constructions (e.g., gypsum boards), comprises the price of paraffin (about €5/kg) and the micro-encapsulated substance (€13/kg).

The disparity between pure PCM and the comprehensive TES system is even greater for active PCM installations. The expenses associated with a calcium-chloride storage system for the heat expelled from a thermally-driven absorption chiller encompass the cost of calcium chloride, which is quite low (€0.3/kg), as well as the expenses for a container, heat exchanger, and additional components, totaling approximately €65/kWh. Materials for thermo-chemical storage (TCS) are costly due to the necessity of preparation, such as pelletisation or layering on supporting structures. The containers and supplementary TCS equipment for heat and mass transfer during energy charging and discharging are also costly. TCS systems can function as either open systems (essentially packed beds of pellets at ambient pressure) or closed systems. Open systems are typically the most economical choice, whereas closed systems require advanced heat exchangers. The TCS cost varies from €8 to €100 per kWh.

6. TES — CONCERNS AND CHALLENGES

ES technologies encounter several obstacles to market introduction, with cost being a significant concern. Additional obstacles are to material characteristics and stability, particularly concerning TCS. Every storage application necessitates a tailored TES design to accommodate certain boundary constraints and requirements. Research and development endeavours concentrate on all thermal

energy storage systems. Most of these R&D initiatives focus on materials (i.e., storage media for various temperature ranges), containers, and the development of thermal insulation. More intricate systems (e.g., PCM, TCS) necessitate research and development endeavours to enhance reactive materials, alongside a deeper comprehension of system integration and process parameters. Market development and penetration fluctuate significantly based on application domains and geographical regions. In Europe, the adoption of TES systems in the building sector is very sluggish, with new construction occurring at approximately 1.3% annually and renovation rates at about 1.5%; hence, the incorporation of TES systems is more feasible during the construction phase. The assessment of European potential relies on a 5% adoption rate of TES systems in edifices. Penetration may be significantly greater in emerging economies due to their elevated rates of new development. The potential of thermal energy storage for co-generation and district heating in Europe is linked to the existing building stock. The co-generation implementation rate is 10.2% (Darkwa et al, 2006), but the implementation of thermal energy storage in these systems is estimated at 15%. In the realm of thermal energy storage (TES) for power applications, a significant area is concentrating solar power, where nearly all new power plants currently operational or under construction are outfitted with TES systems, predominantly utilising molten salt. This may be the most significant advancement submitted for big, centralised thermal energy storage installations. In the industrial sector, around 5% of final energy consumption is estimated to be utilised by thermal energy storage systems. The utilisation of industrial waste heat is anticipated to increase due to the rising costs of fossil fuels, with energy efficiency becoming crucial for competitiveness. The University of Lleida study indicates that the proliferation of TES technologies is anticipated to be substantial in Europe and Asia, especially in Japan, while it is projected to be moderately lower (50%) in the United States. The worldwide potential is approximated to be thrice that of the European potential.

Researchers across are seeking novel and renewable energy sources. One possibility is to develop energy storage devices, which are equally crucial as creating new energy sources. Thermal energy storage is crucial for numerous operations. Latent heat storage is particularly appealing due to its capacity to store substantial energy inside a compact volume while maintaining minimal temperature variation in the medium. Latent heat storage is a novel field of research initiated by Dr Telkes in the 1940s (Lane,1983). It garnered limited attention until the energy crisis of the late 1970s and early 1980s, during which it was actively studied for application in solar heating systems (Lane,1983;Abhat, 1983). As the energy crisis diminished, far less focus was placed on latent heat storage. While investigations into latent heat storage for solar heating systems persist (Kaygusuz, 1999 ; Sari et al, 2000), it is progressively regarded for waste heat recovery and load levelling in power generation (El-Dessouky et al, 1997). Latent heat storage can be achieved via solid-liquid, liquid-gas, solid-gas, and solid-solid phase transitions; however, the only two of practical significance are solid-liquid and solid-solid. The solid-gas and liquid-gas systems possess restricted utility due to the substantial volumes necessitated by these systems. Among the two practical systems, the solid-liquid system is the most extensively researched and widely available in commercial applications. Solid-solid systems exhibit considerable potential, however they have only lately been subjected to investigation (Singer et al, 2010). A multitude of phase change materials (PCMs) have been examined for practical applications. This study compiles extensive practical information on various phase change materials and systems produced utilising latent heat storage technology.

7. THERMAL ENERGY STORAGE

Thermal energy storage can be retained as a variation in the internal energy of a material by sensible heat, latent heat, thermochemical processes, or a combination thereof. In Sensible Heat Storage (SHS), thermal energy is accumulated by increasing the temperature of a solid or liquid. The SHS system employs the heat capacity and the temperature variation of the material during the charging and discharging processes. The quantity of stored thermal energy is contingent upon the specific heat capacity of the medium, the variation in temperature, and the volume of the storage material.

$$Q = \int m C_p dT = m C_{ap} (T_f - T_i) \quad [1]$$

Latent Heat Storage (LHS) relies on the absorption or release of heat during the phase transition of a storage substance between solid and liquid or liquid and gas states. The storage capacity of the LHS system utilising a PCM medium is specified by

$$\begin{aligned} Q &= m a_m \Delta h_m + \int_i^m m C_p dT + \int_m^f m C_p dT \\ &= m [a_m \Delta h_m + C_{sp} (T_m - T_i) + C_{lp} (T_f - T_m)] \end{aligned} \quad (2)$$

LHS systems possess specific advantages over SHS systems. The paramount factor is the increased energy density per unit mass and per unit volume.

Thermochemical systems depend on the energy received and released during the cleavage and reformation of molecular bonds in a fully reversible chemical reaction. The heat stored is contingent upon the quantity of storage material, the endothermic heat of reaction, and the degree of conversion.

$$Q = a_r m \Delta h_r \quad [3] \text{ (Abhat, 1983)}$$

Among the aforementioned thermal heat storage techniques, latent heat thermal energy storage is especially appealing due to its capacity for high energy storage density and its ability to retain heat at a constant temperature corresponding to the phase transition temperature of the phase change material (PCM). Phase transitions may occur in the following forms: solid to solid, solid to liquid, solid to gas, and liquid to gas.

In solid-solid transitions, thermal energy is absorbed during the transformation of one crystalline structure to another. This transition often exhibits reduced latent heat and volume alterations compared to solid-liquid transitions. Solid–solid phase change materials have the benefits of reduced container specifications and enhanced design versatility (Pillai et al, 1976). The most promising materials are organic solid solutions of pentaerythritol, pentaglycerine, Li_2SO_4 , and KHF_2 (Garg et al, 1985). A Trombe Wall constructed with these materials may exhibit superior performance compared to a conventional concrete Trombe Wall.

Solid-gas and liquid-gas transitions exhibit elevated latent heat of phase transition; yet, their significant volume changes during phase transitions present containment challenges, hence limiting their potential application in thermal storage systems. Significant fluctuations in volume render the system convoluted and unfeasible.

Solid-liquid conversions possess relatively lower latent heat than liquid-gas transitions. Nonetheless, these conversions entail a minimal alteration (about 10 percent or less) in volume. Solid-liquid transitions have demonstrated economic viability for application in thermal energy storage systems. Phase Change Materials (PCMs) cannot serve as a heat transmission medium. A heat transfer medium must be utilised with a heat exchanger to transmit energy from the source to the phase change material (PCM) and from the PCM to the load. The heat exchanger must be specifically engineered due to the generally poor thermal diffusivity of phase change materials (PCMs). The volume alterations of the PCMs during melting will require specialised volumetric design of the containers to accommodate the PCM. It must accommodate these volumetric variations and be compatible with the employed PCM. Any latent thermal energy storage system must include at least the following three properties: an appropriate phase change material (PCM)

with a melting point within the needed temperature range, an adequate heat exchange surface, and a compatible container for the PCM.

9. MATERIALS FOR LATENT HEAT STORAGE

Phase Change Materials (PCM) are substances that store latent heat. As the source temperature increases, the chemical bonds inside the PCM disintegrate as the material transitions from solid to liquid, specifically in the context of solid-liquid PCMs, which are of particular importance here. The phase change is an endothermic process, resulting in the absorption of heat by the PCM. When the storage material accumulates heat, it commences melting upon reaching the phase change temperature. The temperature remains constant until the completion of the melting process. The thermal energy retained during the phase transition (melting) of a substance is referred to as latent heat. The impact of latent heat storage presents two primary benefits: 1. It is feasible to accumulate substantial quantities of heat with little temperature variations, hence achieving a high storage density. 2. The phase change at a constant temperature requires time to complete, allowing for the mitigation of temperature fluctuations. They retain 5 to 14 times more thermal energy per unit volume than sensible heat storage materials like water, masonry, or rock (Hale et al, 1971). A significant quantity of phase change materials (PCMs) is recognised to melt with a certain heat of fusion across any desired range. The phase change material (PCM) utilised in the design of thermal storage systems must possess favourable thermophysical, kinetic, and chemical properties (Abhat et al, 1978; Buddhi et al, 1994).

9.1 Thermophysical characteristics

They include:

- a. Melting temperature within the specified operational temperature range.
- b. Elevated latent heat of fusion per unit volume, resulting in a reduced container volume necessary to hold a specified amount of energy.
- c. Elevated specific heat to facilitate substantial sensible heat storage.
- d. Elevated thermal conductivity in both solid and liquid phases to facilitate the energy charging and discharging processes of storage systems.
- e. Minor volume alterations during phase transformation and minimal vapour pressure at operational temperatures to mitigate containment issues.
- f. Consistent melting of the phase change material for a certain storage capacity during each freezing/melting cycle.

9.2 Kinetic characteristics

They include:

- a. High nucleation rate to prevent supercooling of the liquid phase.
- b. Elevated crystal growth rate to ensure the system satisfies the heat recovery requirements from the storage system.

9.3 Chemical characteristics

They include:

- a. Chemical stability.
- b. Complete reversible freeze/melt cycle.
- c. No deterioration following numerous freeze/thaw cycles.
- d. Resistance to corrosion of construction materials.
- e. Materials that are non-toxic, non-flammable, and non-explosive for safety purposes.
- f. Furthermore, the affordability and widespread accessibility of phase transition materials are also crucial.

9.4 Categorisation of Phase Change Materials

A multitude of phase change materials (organic, inorganic, and eutectic) is accessible over any specified temperature range. A taxonomy of phase change materials (PCMs) is presented in the Figure 1.

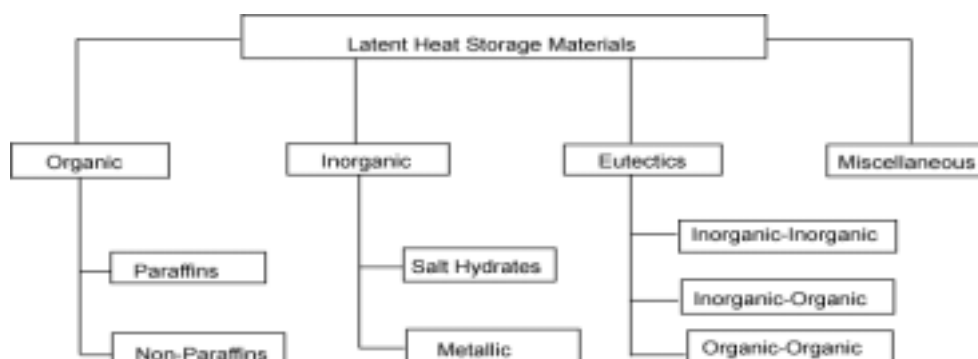


Figure 1. Categorisation of latent heat storage materials

A multitude of organic and inorganic substances can be classified as phase change materials (PCMs) based on their melting temperature and latent heat of fusion. Tables 1 and 2 present the organic and inorganic categories of phase change materials (PCMs), respectively. Since no singular material possesses all the requisite features for optimal thermal storage media, it is necessary to utilise accessible materials and compensate for inadequate physical characteristics through effective system design. Metallic fins can enhance the thermal conductivity of phase change materials (PCMs), supercooling can be mitigated by incorporating a nucleating agent into the storage medium, and incongruent melting can be prevented by employing an appropriate thickness. The distinct thermal and chemical characteristics of each subgroup, which influence the design of latent heat thermal energy storage systems utilising PCMs from that subgroup, are elaborated upon below.

Table 1. List of organic PCMs (94 - 98)

Material	Melting point	Latent heat of fusion (kJ/kg)	Material	Melting point (°C)	Latent heat of fusion (kJ/kg)
N-Tetradeca	5.5	226	N-Penta Cosane	53.7	164
Formic Acid	7.8	247	Myristic Acid	54.0	199
N-Pentadeca	10.0	205	Oxolate	54.3	178
Acetic Acid	16.7	273	Tristearin	54.5	191
N-Hexadeca	16.7	237	O-Xylene	55.0	121
Caprilone	40.0	260	□-Chloroacetic	56.0	147
Docasyle	40.0	201	N-Hexacosane	56.3	255
N-Henicosan	40.5	161	Nitro	56.7	103
Phenol	41.0	120	□-Chloroacetic	61.2	130
N-Lauric	43.0	183	N-Octacosane	61.4	134
P-Joluidine	43.3	167	Palmitic Acid	61.8	164
Cynamide	44.0	209	Bees Wax	61.8	177
N-Docosane	44.5	157	Glyolic Acid	63.0	109
N-Tricosane	47.6	130	P-Bromophenol	63.5	86
Hydrocinna	48.0	118	Azobenzene	67.1	121
Cetyl	49.3	141	Acrylic Acid	68.0	115
O-Nitroanili	50.0	93	Dintro Toluene	70.0	111
Camphene	50.0	239	Phenylacetic	76.7	102
Diphenyl	52.9	107	Thiosinamine	77.0	140

9.5 Paraffins

The normal paraffins, represented by the formula C_nH_{2n+2} , constitute a group of saturated hydrocarbons with highly analogous characteristics. Paraffins ranging from C5 to C15 exist as liquids, while those outside this range are waxy solids. Paraffin wax is the predominantly utilised commercial organic phase change material for thermal energy storage (Lane, 1983; Hale et al, 1971). It primarily comprises straight-chain hydrocarbons with melting points ranging from 23 to 67 °C (Abhat, 1983). Commercial-grade paraffin wax is derived from petroleum distillation and is not a pure product; rather, it is a mixture of several hydrocarbons. Generally, an increase in the average length of the hydrocarbon chain correlates with elevated melting temperatures and heat of fusion (Hiran et al, 1994). Table 3 presents the properties of some paraffins. Paraffins are readily obtainable from numerous producers and are often more costly than salt hydrates (Lane, 1983; Hale et al, 1971).

9.5.1 Benefits

Paraffin waxes exhibit little propensity for segregation. They exhibit chemical stability; nevertheless, Lane (1983) indicates that gradual oxidation occurs upon exposure to oxygen, necessitating the use of closed containers. Sharma et al. (1999) and Sharma et al (2002) indicated consistent characteristics over 1500 cycles in commercial-grade paraffin wax. Paraffin waxes exhibit elevated temps of fusion, as demonstrated in the Table. 3.

They also lack inclinations towards supercooling, rendering nucleating agents unnecessary (Lane, 1983; Hale et al., 1971). Paraffin waxes are nontoxic and inert. They are compatible with all metallic containers and may be seamlessly integrated into thermal storage systems (Lane, 1983). Precautions should be exercised while utilising plastic containers, since paraffins may permeate and compromise the integrity of certain plastics (Lane, 1983).

9.5.2 Disadvantages

Paraffins exhibit limited thermal conductivity in their solid form, as demonstrated in Table 4. This is a challenge when elevated heat transfer rates are necessary during the freezing stage. Veraj et al. (1998) indicates that this issue can be mitigated by employing finned containers and metallic fillers or by utilising combined latent/sensible storage methods. Aluminium honeycombs have been shown to enhance system performance (Hale et al, 1971). Paraffins exhibit a significant volumetric variation between their solid and liquid phases. This engenders numerous issues in container design (Hasnain, 1998). Paraffins are combustible; this risk can be effectively mitigated through the use of an appropriate container (Hiran et al, 1994; Hasnain, 1998). Lane ((1983) additionally indicates that paraffins may compress sufficiently to detach from the walls of the storage container, significantly reducing heat storage capability. In contrast to salt hydrates, commercial paraffins typically lack distinct and precise melting points.

Abhat (1983) indicates melting ranges of 43 °C. This results from the combination of materials and a solid-solid phase transformation in commercial-grade paraffins just prior to melting, which retains a significant amount of the material's latent heat capacity (Abhat, 1983). This diminishes the efficiency of the heat storage system, as it is no longer isothermal.

9.6 Non-paraffins

This constitutes the predominant group of candidates' materials for phase change storage. Lane et al. (1983); Lane (1978); Lane (1989); Buddhi et al. (1994, Abhat (1983) and Buddhi (12) have performed a comprehensive examination of organic materials, identifying several esters, fatty acids, alcohols, and glycols appropriate for energy storage. These materials are combustible and must not be subjected to elevated temperatures, fires, or oxidising agents. Non-paraffins are included in Table 4.

9.7 Lipids

Fatty acids, defined by the chemical formula $\text{CH}_3(\text{CH}_2)_n\text{COOH}$, exhibit similar properties to paraffins. Their benefits of more acute phase transitions are counterbalanced by the drawback of approximately threefold the expense of paraffins (Hasnain, 1998). They are also mildly corrosive. Table 5 enumerates several fatty acids pertinent to latent heat thermal energy storage applications at low temperatures. Sharma et al., (1999; 2002) indicates consistent characteristics following 1500 cycles for stearic acid.

9.8 Hydrated Salts

Salt hydrates are among the earliest and most extensively researched phase change materials for thermal energy storage. They comprise a salt and water that amalgamate into a crystalline matrix during solidification. They can be utilised individually or in eutectic combinations (Abhat, 1983). Table 6 presents the properties of some salt hydrates. Numerous materials possess melting temperatures between 15 and 117 °C (Lane, 1983). Salt hydrates constitute the most significant category of phase change materials (PCMs), which have been thoroughly investigated for their application in latent heat thermal energy storage systems. Three categories of melted salt behaviour can be distinguished: congruent, incongruent, and semi-congruent melting.

9.8.1 Benefits

The low cost and easy accessibility of salt hydrates render them commercially appealing for thermal energy storage applications. Calcium chloride hexahydrate ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$) and sodium sulphate decahydrate ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) are among the most economical and readily accessible salt hydrates. Numerous salt hydrates are cost-effective for storage applications (Lane, 1978). Salt hydrates has a distinct melting point, hence optimising the efficacy of a thermal energy storage device. They have superior thermal conductivity relative to other heat storage phase change materials (PCMs). This can enhance thermal transport into and out of the storage unit. They possess a substantial heat of fusion to minimise the required dimensions of the storage system. Salt hydrates exhibit a reduced volumetric variation compared to alternative phase change materials (PCMs).

9.8.2 Disadvantages

Segregation refers to the production of alternative hydrates or dehydrated salts that tend to precipitate, hence diminishing the active volume available for thermal storage. Abhat (Abhat, 1983) indicates a reduction above 73% in the heat of fusion of $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ over 1000 melt/freeze cycles. This issue can be mitigated to some degree by employing gelled or thicker mixes (Lane, 1983), although this method adversely affects the thermal storage properties of the combination, and the mixture continues to deteriorate over time (Abhat, 1983). Salt hydrates exhibit supercooling due to their inability to initiate crystallisation at the phase change material's freezing point. This may involve refraining from the use of appropriate nucleating agents to initiate crystal formation in the storage medium. Lane (1983) provided an exhaustive catalogue of nucleating agents for the majority of prevalent salt hydrates. Abhat (1983) indicated material degradation in $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ after merely two cycles when the test sample was not hermetically sealed. Consequently, it is essential to design containers that retain the content while preventing water leakage. Another issue with salt hydrates is their propensity to induce corrosion in metal containers frequently utilised in thermal storage systems (Abhat, 1983). The compatibility of PCM and the container must always be verified prior to use.

9.9 Eutectics

A eutectic is the mixture with the lowest melting point among two or more components, all of which melt and solidify congruently. Eutectic compositions often melt and solidify without segregation, as they crystallise into a homogeneous mixture, minimising the potential for component separation. Upon melting, the components liquefy concurrently. Table 7 presents a compilation of eutectic substances.

Table 2. Inventory of Inorganic Phase Change Materials (1, 2, 12, 94 - 98)

Name	Melting point (°C)	Latent heat of fusion (kJ/kg)	Name	Melting point (°C)	Latent heat of fusion (kJ/kg)
H ₂ O	0.0	333	Bi ₃	31.8	10
POCl ₃	1.0	85	SO ₃ (β)	32.3	151
D ₂ O	3.7	318	TiBr ₄	38.2	23
SbCl ₅	4.0	33	H ₄ P ₂ O ₆	55.0	213
H ₂ SO ₄	10.4	100	SO ₃ (γ)	62.1	331
IC 1 (β)	13.9	56	SbCl ₃	73.4	25
MOF6	17.0	50	NaNO ₃	307	172 – 199
SO ₃ (α)	17.0	108	KNO ₃	333 - 380	116 – 266
IC 1 (□)	17.2	69	KOH	380	149
P ₄ O ₆	23.7	64	MgCl ₂	714 - 800	452 – 492
H ₃ PO ₄	26.0	147	NaCl	800 - 802	466 – 492
Cs	28.3	15	Na ₂ CO ₃	854	275
Ga	30.0	80	KF	857	452
AsBr ₃	30.0	38	K ₂ CO ₃	897	235

Table 3. Melting point and latent heat of fusion of paraffins (1, 2, 12, 94 - 99)

Name	No. of "C"	Melting point (°C)	Density (kg/m ³)	Thermal Conductivity (W/m·K)	Latent heat of fusion (kJ/kg)
n - Dodecane	12	-12	750		n.a.
n - Tridecane	13	-6	756	0.21 ^S	n.a.
n - Tetradecane	14	4.5 - 5.6	771		231
n - Pentadecane	15	10	768	0.17	207
n - Hexadecane	16	18.2	774	0.21 ^S	238
n - Heptadecane	17	22	778		215
n - Octadecane	18	28.2	814 ^{S(14)}	0.35 ^{S (14)}	245
n - Nonadecane	19	31.9			222
n - Eicosane	20	37			247
n - Heneicosane	21	41			215
n - Docosane	22	44	912 ^S , 769 ^L	0.21 ^S	249
n - Tricosane	23	47			234
n - Tetracosane	24	51			255
n - Pentacosane	25	54			238
Paraffin Wax	n.a.	32	785 ^{S(15)}	0.514 ^{S(15)}	251(15)
n - Hexacosane	26	56	770		257
n - Heptacosane	27	59	773		236
n - Octacosane	28	61			255
n - Nonacosane	29	64	910 ^S , 765 ^L	0.21 ^S	240
n - Triacontane	30	65			252
n - Dotricontane	31	n.a.			n.a.
n - Triticontane	32	70	930 ^S , 830 ^L		n.a.
	33	71			189

S: solid; L: liquid; n.a.: not available

Table 4. Melting point and latent heat of fusion of non - paraffins (1, 2, 12, 94 - 99)

Name	Melting point (^o C)	Density (kg/m ³)	Latent heat of fusion (k J/ kg)
Formic Acid	7.8	1226.7 ^{15C}	247
Acetic Acid	16.7	1050 ^{20C}	187
Glycerin	17.9	1260 ^{20C}	198.7
Lithium Chloride Ethanolate	21	n.a.	188
Polyethylene Glycol 600	20-25	1100 ^{20C}	146
D – Lactic Acid	26	1249 ^{15C}	184
1-3 Methyl Pentacosane	29	n.a.	197
Camphenilone	39	n.a.	205
Docasyl Bromide	40	n.a.	201
Caprylone	40	n.a.	259
Heptadecanone	41	n.a.	201
1-Cyclohexyloctadecane	41	n.a.	218
4-Heptadecanone	41	n.a.	197
Cyanamide	44	1080 ^{20C}	209
Methyl Eicosanate	45	851 ^{79C}	230
3-Heptadecanone	48	n.a.	218
2-Heptadecanone	48	n.a.	218
Camphene	50	842 ^{54C}	238
9-Heptadecanone	51	n.a.	213
Methyl Behenate	52	n.a.	234
Pentadecanoic Acid	52.5	n.a.	178
Hypophosphoric Acid	55	n.a.	213
Chloroacetic Acid	56	1580 ^{20C}	130
Trimyristin	33-57	862 ^{20C}	201-213
Heptaudecanoic Acid	60.6	n.a.	189
Bee Wax	61.8	950	177
Glycolic Acid	63	n.a.	109
Oxazoline-Wax-TS 970	74	n.a.	
Arachic Acid	76.5	n.a.	227
Bromcamphor	77	1449 ^{81C}	174
Durene	79.3	838 ^{20C}	156
Acetamide	81	1159	241
Methyl Brombrenzoate	81	n.a.	126
Alpha Naphthol	96	1095 ^{98.7C}	163
Glutaric Acid	97.5	1429	156
p-Xylene Dichloride	100	n.a.	138.7
Methyl Fumarate	102	1045	242
Catechol	104.3	1370 ^{15C}	207
Quinone	115	1318 ^{20C}	171
Acetanilide	115	1210 ^{4C}	142
Succinic Anhydride	119	1104	204
Benzoic Acid	121.7	1266 ^{15C}	142.8
Stibene	124	1164 ^{15C}	167
Benzamide	127.2	1341	169.4
Phenacetin	137	n.a.	136.7
Alpha Glucose	141	1544	174
Acetyl – p- Toluidene	146	n.a.	180
Phenylhdrazone Benzaldehy	155	n.a.	134.8

Salicylic Acid	159	1443 ^{20C}	199
Benzanilide	161	n.a.	162
O-Mannitol	166	1489 ^{20C}	294
Hydroquinone	172.4	1358 ^{20C}	258
p- Aminobenzoic Acid	187	n.a.	153

Table 5. Melting point and latent heat of fusion: Fatty acids (1, 2, 12, 94 - 99)

Name	Melting point (°C)	Density (kg/m ³)	Thermal conductivity (W/mK)	Latent heat of fusion (kJ/kg)
Propyl Palmiate	10	n.a.	n.a.	186
Isopropyl Palmiate	11	n.a.	n.a.	100
Oleic Acid	13.5 - 16.3	863 ^{60C}	n.a.	n.a.
Isopropyl Stearate	14 - 19	n.a.	n.a.	140 – 142
Caprylic Acid	16	901 ^{30C}	0.149 ^{39C}	148
Butyl Stearate	19	n.a.	n.a.	140
Dimethyl Sabacate	21	n.a.	n.a.	120 – 135
Myristic Acid +	24	888 ^{25C}	0.164 ^{39C}	147.7
Vinyl Stearate	27 - 29	n.a.	n.a.	122
Methyl Palmitate	29	n.a.	n.a.	205
Capric Acid	32	878 ^{45C}	0.153 ^{38.5C}	152.7
Erucic Acid	33	853 ^{70C}	n.a.	n.a.
Lauric Acid	42 - 44	862 ^{60C}	n.a.	178
Elaidic Acid	47	851 ^{79C}	n.a.	218
Pelargonic Acid	48	n.a.	n.a.	n.a.
Myristic Acid	49 - 51	861 ^{55C}	n.a.	205
Palmitic Acid	64	850 ^{65C}	0.162 ^{68.4C}	185.4
Stearic Acid	69	848 ^{70C}	0.172 ^{70C}	202.5
Valporic Acid	120	n.a.	n.a.	n.a.

Table 6. Melting point and latent heat of fusion of salt hydrates (1, 2, 12, 94 - 99)

Name	Melting Point (°C)	Density (kg/m ³)	Thermal Conductivity (W/m K)	Latent Heat (kJ/kg)	Melting Behavior ^a (13)
LiClO ₃ .3H ₂ O	8	n.a.	n.a.	253	C
NH ₄ Cl.Na ₂ SO ₄ .10H ₂ O	11	n.a.	n.a.	163	n.a.
K ₂ HO ₄ .6H ₂ O	14	n.a.	n.a.	108	c
NaCl.Na ₂ SO ₄ .10H ₂ O	18	n.a.	n.a.	286	n.a.
KF.4H ₂ O	18	n.a.	n.a.	330	c
K ₂ HO ₄ .4H ₂ O	18.5	1447 ^{20C}	n.a.	231	n.a.
Mn(NO ₃) ₂ .6H ₂ O	25	1738 ^{20C} (12)	n.a.	148	n.a.
LiBO ₂ .8H ₂ O	25.7	n.a.	n.a.	289	n.a.
FeBr ₃ .6H ₂ O	27	n.a.	n.a.	105	n.a.
CaCl ₂ .6H ₂ O	29 –	1562 ^{32C}	0.561 ^{61.2C}	170	- Ic
LiNO ₃ .3H ₂ O	30	n.a.	n.a.	189	- C
Na ₂ SO ₄ .10H ₂ O	32	1485 ^{24C}	0.544	251	- Ic
Na ₂ CO ₃ .10H ₂ O	33 –	1442	n.a.	247	Ic
KFe(SO ₄) ₂ .12H ₂ O	33	n.a.	n.a.	173	Ic

CaBr ₂ .6H ₂ O	34	1956 ^{35C}	n.a.	115	-	n.a.
LiBr.2H ₂ O	34	n.a.	n.a.	124		Ic
Na ₂ HPO ₄ .12H ₂ O	35	1522	n.a.	256	-	Ic
Zn(NO ₃) ₂ .6H ₂ O	36	1828 ^{36C}	0.464 ^{39.9C}	134	-	C
Mn(NO ₃) ₂ .4H ₂ O	37	n.a.	n.a.	115		n.a.
FeCl ₃ .6H ₂ O	37	n.a.	n.a.	223		C
CaCl ₂ .4H ₂ O	39	n.a.	n.a.	158		Ic
CoSO ₄ .7H ₂ O	40.7	n.a.	n.a.	170		n.a.
CuSO ₄ .7H ₂ O	40.7	n.a.	n.a.	171		n.a.
KF.2H ₂ O	42	n.a.	n.a.	162	-	C
MgI ₂ .8H ₂ O	42	n.a.	n.a.	133		n.a.
CaI ₂ .6H ₂ O	42	n.a.	n.a.	162		n.a.
Ca(NO ₃) ₂ .4H ₂ O	43 – 47	n.a.	n.a.	106	-	C
Zn(NO ₃) ₂ .4H ₂ O	45	n.a.	n.a.	110		n.a.
K ₃ PO ₄ .7H ₂ O	45	n.a.	n.a.	145		n.a.
Fe(NO ₃) ₃ .9H ₂ O	47	n.a.	n.a.	155	-	Ic
Mg(NO ₃) ₃ .4H ₂ O	47	n.a.	n.a.	142		n.a.
Na ₂ SiO ₃ .5H ₂ O	48	n.a.	n.a.	168		n.a.
Na ₂ HPO ₄ .7H ₂ O	48	n.a.	n.a.	135	-	Ic
Na ₂ S ₂ O ₃ .5H ₂ O	48	1600	n.a.	209		n.a.
K ₂ HPO ₄ .3H ₂ O	48	n.a.	n.a.	99		n.a.
MgSO ₄ .7H ₂ O	48.4	n.a.	n.a.	202		n.a.
Ca(NO ₃) ₂ .3H ₂ O	51	n.a.	n.a.	104		n.a.
Na(NO ₃) ₂ .6H ₂ O	53	n.a.	n.a.	158		n.a.
Zn(NO ₃) ₂ .2H ₂ O	55	n.a.	n.a.	68		C
FeCl ₃ .2H ₂ O	56	n.a.	n.a.	90		n.a.
CO(NO ₃) ₂ .6H ₂ O	57	n.a.	n.a.	115		n.a.
Ni(NO ₃) ₂ .6H ₂ O	57	n.a.	n.a.	168		n.a.
MnCl ₂ .4H ₂ O	58	n.a.	n.a.	151		n.a.
CH ₃ COONa.3H ₂ O	58	n.a.	n.a.	270	-	Ic
LiC ₂ H ₃ O ₂ .2H ₂ O	58	n.a.	n.a.	251-377		n.a.
MgCl ₂ .4H ₂ O	58.0	n.a.	n.a.	178		n.a.
NaOH.H ₂ O	58	n.a.	n.a.	272		n.a.
Na(CH ₃ COO).	58	n.a.	n.a.	n.a.		n.a.
Cd(NO ₃) ₂ .4H ₂ O	59	n.a.	n.a.	98		n.a.
Cd(NO ₃) ₂ .1H ₂ O	59.5	n.a.	n.a.	107		n.a.
Fe(NO ₃) ₂ .6H ₂ O	60	n.a.	n.a.	125		n.a.
NaAl(SO ₄) ₂ .1H ₂ O	61	n.a.	n.a.	181		Ic
FeSO ₄ .7H ₂ O	64	n.a.	n.a.	200		n.a.
Na ₃ PO ₄ .12H ₂ O	65	n.a.	n.a.	168		n.a.
Na ₂ B ₄ O ₇ .10H ₂ O	68	n.a.	n.a.	n.a.		n.a.
Na ₃ PO ₄ .12H ₂ O	69	n.a.	n.a.	n.a.		n.a.
LiCH ₃ COO.2H ₂ O	70	n.a.	n.a.	150	-	C
Na ₂ P ₂ O ₇ .10H ₂ O	70	n.a.	n.a.	186	-	Ic
Al(NO ₃) ₂ .9H ₂ O	72	n.a.	n.a.	155	-	Ic
Ba(OH) ₂ .8H ₂ O	78	1937 ^{84C}	0.653 ^{85.7C}	265	-	C
Al ₂ (SO ₄) ₃ .18H ₂ O	88	n.a.	n.a.	218		Ic
Sr(OH) ₂ .8H ₂ O	89	n.a.	n.a.	370		Ic
Mg(NO ₃) ₂ .6H ₂ O	89 – 90	1550 ^{94C}	0.490 ^{95C}	162	-	C

KAl	91	n.a.	n.a.	184	n.a.
(NH ₄)Al(SO ₄).	95	n.a.	n.a.	269	n.a.
Na ₂ S.51/2H ₂ O	97.5	n.a.	n.a.	n.a.	n.a.
LiCl.H ₂ O	99	n.a.	n.a.	212	Ic
CaBr ₂ .4H ₂ O	110	n.a.	n.a.	n.a.	n.a.
Al ₂ (SO ₄) ₂ .16H	112	n.a.	n.a.	n.a.	n.a.
MgCl ₂ . 6H ₂ O	115	–	1450 ^{120C}	165	- n.a.
NaC ₂ H ₃ O ₂ .3H	137		1450	172	n.a.

9.10 Cross-linked Polyethylene

Cross-linked Polyethylene resembles the polyethylene utilised in plastic bottles, with the distinction that it is minimally cross-linked to inhibit liquefaction upon melting. Similar to a liquid-solid phase change material, it stores energy through the formation and disruption of crystalline structures. The characteristics of two cross-linked polyethylene samples are presented in Table 8. In contrast to a liquid-solid phase change material, it possesses a stable form and can be utilised without encapsulation.

9.10.1 Benefits

Despite being more expensive than alternative phase change materials (PCMs), a lower cost is essential for the complete heat storage system, offering greater feasibility compared to other PCMs (Lane,1983). Cross-linked polyethylene is non-toxic and predominantly chemically inert.

9.10.2 Disadvantages

The working temperatures of 110 to 140 °C are excessively high for several applications, including space and water heating. To the author's knowledge, no company has commercially produced cross-linked polyethylene for thermal energy storage applications at this time.

9.11 Polyols

Research has also been conducted at playschools (lane, 1983). Polyols retain energy by transitioning from a heterogeneous state at lower temperatures to a face-centered cubic structure at elevated temperatures (Wangm, 2000). Polyols offer numerous advantages over solid-liquid phase change materials, including little volume alteration, absence of leakage, and material stability. These benefits are accompanied by the drawbacks of low latent heat, elevated phase change temperatures, and increased cost. Wang (2000) describes a method for integrating polyalcohols to modify operational temperatures. Table 8 presents some of his findings for the Neopentyl Glycol (NPG)/Pentaerythritol (PE) and Neopentyl Glycol (NPG)/Trihydroxy Methyl-Aminomethane (TAM) systems.

10. LATENT HEAT STORAGE SYSTEMS

The fluctuating and variable characteristics of solar irradiation, along with the necessity to employ solar energy systems for consistent and stable loads, render storage systems indispensable for the majority of solar energy applications. Latent heat storage is of particular relevance among the many heat storage techniques when compared to sensible heat storage. Phase change materials (PCMs) are utilised in solar energy storage systems for water heating, greenhouses, building climate control, cooking, and waste heat recovery systems.

10.1 Solar Water Heating

Solar water heaters are gaining popularity due to their relative affordability and ease of fabrication and maintenance. Prakesh et al. (1985) examined a built-in storage water heater featuring a layer of phase change material (PCM) at the bottom (Figure 2).

During daylight hours, the water is heated, thus transferring thermal energy to the PCM beneath it. The PCM absorbs energy as latent heat and undergoes melting. During non-sunlight hours,

heated water is replaced with cold water, which absorbs energy from the PCM. The energy is released by the PCM during its phase transition from liquid to solid. This method may lack efficacy due to inadequate heat transmission between the phase change material and water.

Table 7. List of organic and inorganic eutectics (1, 2, 10, 12, 94 - 99)

Name	Composition	Melting	Latent	Heat	of
Na ₂ SO ₄ +NaCl+KCl+H ₂ O	31+13+16+40	4	234		
Na ₂ SO ₄ +NaCl+NH ₄ Cl+H ₂ O	32+14+12+42	11	n.a.		
C ₅ H ₅ C ₆ H ₅ + (C ₆ H ₅) ₂ O	26.5+73.5	12	97.9		
Na ₂ SO ₄ +NaCl+H ₂ O	37+17+46	18	n.a.		
Na ₂ S ₄ +MgSO ₄ +H ₂ O	25+21+54	21 – 24	n.a.		
C ₁₄ H ₂₈ O ₂ + C ₁₀ H ₂₀ O ₂	34 + 66	24	147.7		
Ca(NO) ₃ .4H ₂ O	+ 47 + 53	30	136		
NH ₂ CONH ₂ + NH ₄ NO ₃	-	46	95		
Mg(NO ₃) ₂ .6H ₂ O + NH ₄	61.5 +38.4	52	125.5		
Mg(NO ₃) ₂ .6H ₂ O	+ 58.7 + 41.3	59	132.2		
Mg(NO ₃) ₂ .6H ₂ O	+ 53 +47	61	148		
Mg(NO ₃) ₂ .6H ₂ O	+ 59 + 41	66	168		
Napthalene + Benzoic Acid	67.1 + 32.9	67	123.4		
AlCl ₃ +NaCl+ZrCl ₂	79+17+4	68	234		
AlCl ₃ +NaCl+KCl	66+20+14	70	209		
NH ₂ CONH ₂ + NH ₄ Br	66.6 + 33.4	76	151		
LiNO ₃ + NH ₄ NO ₃ +	25 + 65 + 10	80.5	113		
AlCl ₃ +NaCl+KCl	60+26+14	93	213		
AlCl ₃ +NaCl	66+34	93	201		
NaNO ₂ +NaNO ₃ +KNO ₃	40+7+53	142	n.a.		

Table 8. Melting point and latent heat of fusion of some selected solid - solid PCMs (1, 2, 10, 94- 99)

Name	Melting point (°C)	Latent heat of fusion (J/kg)
38.2%NPG/61.8%PE	26 – 32	18 – 75
38.2%NPG/61.8%TAM	22 – 35	27 – 33
76.4%NPG/33.6%TAM	28 – 38	75 – 80
76.4%NPG/33.6%PE	31 – 37	35 – 46
91%NPG/9%PE	31 – 36	68
91%NPG/9%TAM	30 – 39	143 – 150
Neopentyl Glycol(NPG)	43	130
Diannopentacrythritol	68	184
2-Amino - 2 - Methyl - 1, 3 -	78	264
2 - Methyl - 2 - Mtro - 1, 3 - Propanediol	79	201
Trumethylolethane	81	192
Pentaglycerin	81	192
2-Hydroxymethyl-2-Methyl-1, 3 -	81	192
Monoaminopentaerythritol	86	192
Cross-Linked Polyethylene	110 – 115	125 – 146
Tris(Hydroxymethyl)Acetic Acid	124	205
2-Amino-2-Hydroxymethyl-1, 3 -	131	285
Cross-Linked HDPE	125 – 146	167 – 201
2,2-Bis(Hydroxymethyl) Propionic	152	289
38.2%NPG/61.8%PE	170	147
Penterythritol(PE)	185	303

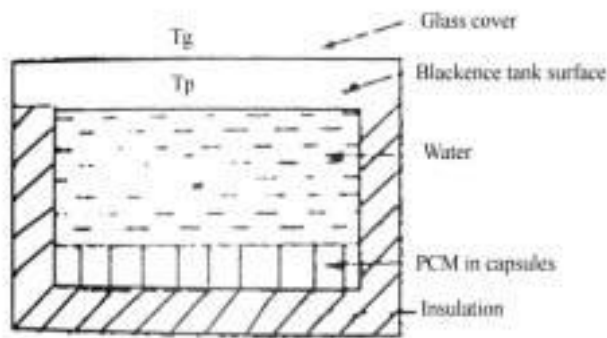


Figure 2. Integrated storage heater with a phase change material layer

Bansal and Buddhi (1992) theoretically examined a cylindrical storage unit within a closed loop using a flat plate collector (Fig. 3) for its charging and discharging modes. A theoretical model for a cylindrical latent heat storage system was constructed. The computations for the interface moving boundary and fluid temperature were conducted utilising paraffin wax (p-116) and stearic acid as phase transition materials. Tiwari et al. (1988) conducted an investigation of a phase change material (PCM) storage system for water heaters, integrating the impact of water flow through a parallel plate situated at the solid-liquid interface. Movable insulation has been developed to minimise nocturnal heat losses from the exposed surface. They determined that the hot water (temperature $15\text{--}20\text{ }^{\circ}\text{C} > T_a$) can be maintained continuously, and that temperature fluctuations diminish as the melted area of the PCM water heater increases. Tayed et al. (1993) devised a home hot water system utilising $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ as a phase change material and contrasted it with a simulation model that determines the optimal flow rate of the intake water supply necessary to sustain a constant outlet water temperature. Font et al. (1994) performed an initial investigation into the design of a device for domestic water utilising solid-solid phase change materials (PCM). Numerical simulation was conducted utilising a unidirectional model and validated against the experimental results. The agreement between experimental and simulation data indicates that this model is suitable for investigating the heat transfer phenomenon in the PCM to optimise device design.

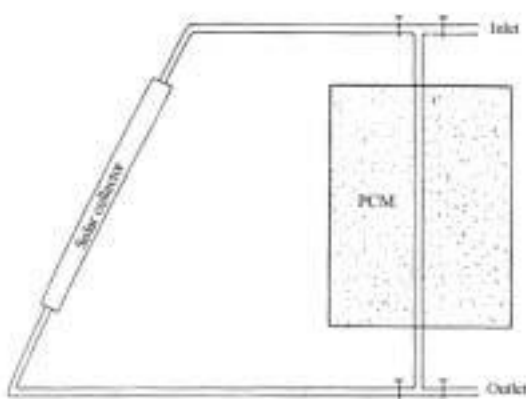


Figure 3. A residential hot water system including distinct phase change material (PCM) heat storage.

Chauarsia (1986) and Gu et al. (2004) indicated that paraffin wax may serve as a storage medium for solar water heating. Baran and Sari (2003) indicated that the eutectic mixture of palmitic acid (64.2 wt%) and stearic acid (35.8 wt%), with a melting point of $52.3\text{ }^{\circ}\text{C}$ and a latent heat of fusion of 182 kJ/kg , is appropriate for residential water heating applications. Bhargava et al. (1983) employed phase change materials in a solar water heater and determined that the system's efficiency and the outlet water temperature during nighttime hours improve with enhanced

thermal conductivity of the solid-liquid phases of the materials. Hasan et al. (1994) have examined various fatty acids as phase change materials for residential water heating. They suggested that myristic acid, palmitic acid, and stearic acid, which have melting temperatures ranging from 50 °C to 70 °C, are suitable phase transition materials for water heating. The thermophysical properties of the identified phase change materials (PCMs) were assessed using differential scanning calorimetry (DSC). The researchers determined that a minor decrease in latent heat occurred after 450 heating cycles (20–80°C), whereas a drop of up to one-third of the latent heat was observed after 21 heating cycles (20–150°C).

Kurklu et al. (2002) created an innovative water - PCM solar collector, and its short-term thermal performance was examined (Figure 4). The solar collector had two adjacent parts, one containing water and the other containing a phase change material (Paraffin Wax, 45–50 °C). The study's results revealed that the water temperature surpassed 55 °C on a normal day of elevated solar radiation and remained above 30 °C throughout the night. The current solar collector offers significant advantages over conventional solar hot water collectors in Turkey, particularly for overall system weight and cost. This sort of collector may utilise PCM-water solar panels on the southern facades of buildings for energy storage purposes.

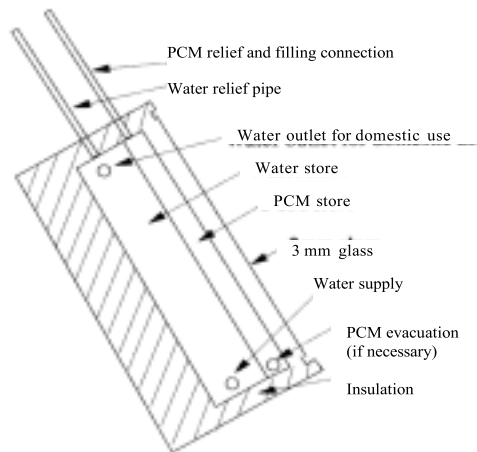


Figure 4. Water - Phase Change Material Solar Collector

10.2 Heating

Jurinak and Khalik (1978) and Khalik et al (1978) have examined the impact of phase change materials on the efficacy of an air-based solar heating system. The primary finding was that the phase change material (PCM) should be chosen based on its melting temperature rather than its latent heat, as the melting temperature significantly influences system performance. They also indicated that systems employing $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ necessitate approximately half the storage volume of a traditional water tank system. An efficient heat capacity for the latent heat storage unit was derived as a function of its mass, latent heat, specific heat, and melting temperature. The effective heat capacity can be employed to assess the thermal performance of the system utilising phase change materials (PCM). Klein and Beckman (1979) conducted simulation research on a closed-loop solar thermal system applicable for several uses, including room heating, absorption air conditioning, and certain forms of process heating. This design methodology can be employed to evaluate the long-term efficacy of such systems. Bulkin et al. (1988) proposed a mathematical model for the design of a solar heating and hot-water supply system utilising solar absorbers and a heat pump with two thermal-storage tanks, considering the system's interaction with external climatic conditions and the serviced room. Ghoneim et al. (1979) examined the impact of assumptions in previous models on the proportion of the demand satisfied by solar energy and the necessary storage capacities.

Kaygusuz et al. (1991) created an experimental model to analyse the dynamics of a solar-assisted heat pump, collectors, drier, and energy storage tank utilised for grain drying. Kaygusuz et al (1995) examined the efficacy of a dual-source heat pump system for domestic heating (Figure 5). In the dual-source configuration, the evaporator is engineered to harness energy from either the atmosphere or the solar energy reservoir. He determined that the dual source system could conserve more energy than both the parallel and series systems. Kaygusuz (1995) performed both experimental and theoretical investigations to assess the efficacy of phase-change energy storage materials, as well as the fluctuation of outlet fluid temperature corresponding to varying NTU (number of transfer units of the storage unit) values in water-based solar heating systems (Figure 6). This system comprises a solar collector, energy storage tank, water-to-air heat exchanger, auxiliary electric heater, water circulation pump, and additional measurement and control apparatus.

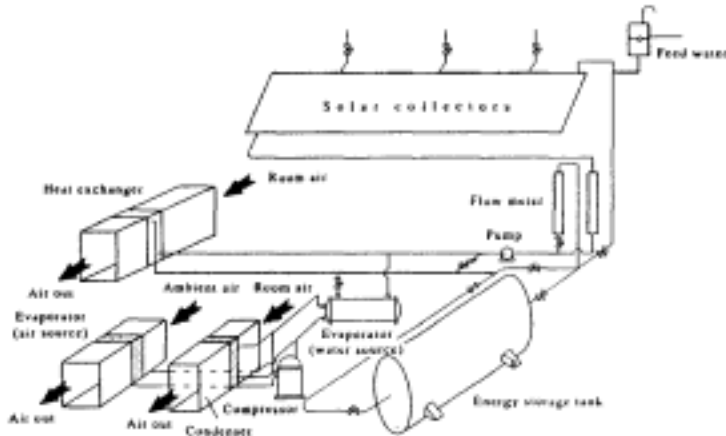


Figure 5. Solar-assisted heat pump system connected to energy storage tank

Solar energy is gathered and directed to the energy storage tank, which contains 1500 kg of encapsulated phase change material (PCM), while the heat transfer fluid (water) circulates alongside it (Figure 7). Through experimental and theoretical analyses, they determined that heat storage is a crucial element in temperate climates (e.g., Trabzon, Turkey), and that $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ or $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ can serve as phase change materials, offering a favourable alternative to rock and water storage systems. PCM storage is more advantageous as a heat source for a heat pump compared to water and rock storage, as the energy storage temperature of PCM is approximately 25-35°C for both $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ and $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$. This temperature range is appropriate for solar-assisted heat pump applications in Turkey. Mehmet (Mehmet et al, 2000) examined the thermal efficacy of a solar-assisted latent heat storage system employed for space heating in conjunction with a heat pump, utilising 1090 kg of encapsulated phase change material ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$). He determined that the shorter and narrower pipe should be utilised for optimal heating at the outset of the studies. Faith et al. (1995) designed a straightforward solar air heater coupled with a thermal energy storage device, as illustrated in the Figure 8. Heat storage materials were introduced into the tubes and designated as the absorber of the collector. Paraffin wax (melting point 50 °C, latent heat of fusion 190 kJ/kg) and $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ (melting point 32 °C, latent heat of fusion 251 kJ/kg) are utilised as phase change materials (PCMs). These systems augment the heat transfer area, enhance the coefficient, and diminish radiation and convection losses. Through a fundamental transient analysis, precise formulas for the temperatures of the heater absorber and glass cover, effective heat gain, outlet air temperature, and heater efficiency have been formulated as a function of time. The system with integrated PCM can deliver heat load continuously for 24 hours a day at a nearly constant temperature. The daily average efficiency of paraffin wax is around 63.35%, in contrast to 59% for sand as the storage medium and 38.7% for the traditional flat plate heater system.

Strith et al. (2002) employed Transparent Insulation Material (TIM) and transparent phase change material (PCM) within the wall to heat the air for residential ventilation. Paraffin wax (melting point 25-30 °C, latent heat of fusion 150 kJ/kg) served as a phase change material, with

60 kg incorporated into a panel for space heating. The average efficiency of solar energy absorbed by the PCM and subsequently transferred to the ventilation air was 45%. Manz et al. (1997) have performed a similar work utilising a different phase change material ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$). He created a numerical simulation that aligns closely with experimental findings. He also indicated that the greatest time ratio parameter may be attained with a mean melting temperature of roughly 20 to 21°C when the building does not experience energy loss through the south-facing TIM-PCM wall.

Arkar et al. (2002) developed a solar-assisted ventilation system utilising phase change material (PCM) storage. He suggested that paraffin spherical encapsulations create a uniform porosity effect in ventilation ducts, hence enhancing the thermal conductivity of paraffin. He stated that ambient air temperature could decrease by 3 to 4 K on a clear summer night.

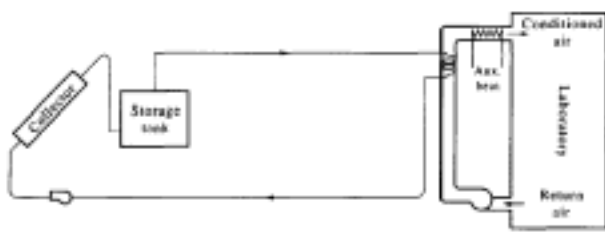


Figure 6. Schematic representation of the fundamental solar energy system

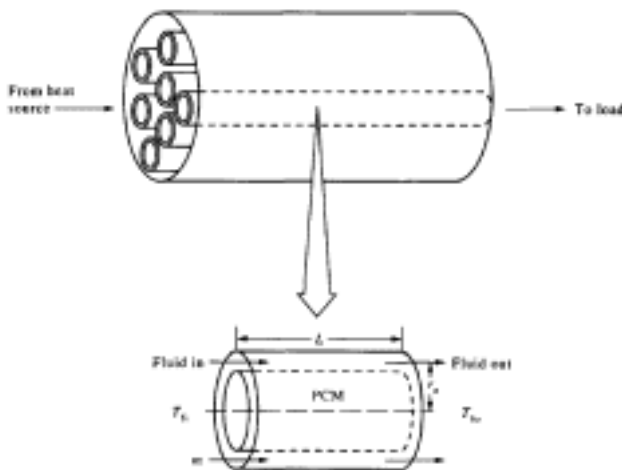


Figure 7. Schematic representation of the latent heat storage tank

Ismail and Alves (1986) reported a theoretical model of a shell-and-tube phase change material storage unit. The energy equation for the phase change material (PCM) is expressed in terms of enthalpy. The numerical findings demonstrate the influence of the Biot number, the relative diameters of the tubes, and the inlet fluid temperature on the thermal performance of the system. Visser (1986) formulated a component model for the numerical characterisation of two distinct short-term heat storage vessels. In both containers, energy is stored as the latent heat of phase change materials (PCMs). The transient simulation program was employed to evaluate the efficacy of the cylindrical energy storage tank utilised in the solar-assisted residential heating system with a heat pump. Yimmer et al. (1989) created a numerical model to optimise a fundamental one-dimensional shell-and-tube thermal energy storage system. An enthalpy method was utilised for the phase change material (PCM). A parametric analysis was conducted to evaluate the impact of the inner tube and outer shell radii, as well as the thermal conductivity of the liquid phase of the PCM, on the unit's performance. Lacroix (1993) constructed a theoretical model to forecast the transient behaviour of a shell-and-tube storage unit, with the phase change material on the shell side and the heat transfer fluid cycling within the tubes. Subsequently, parametric studies are conducted to evaluate the impact of diverse thermal and geometric parameters on the heat transfer process and the system's behaviour.

Sagara et al. (1994) evaluated the long-term efficacy of an air-based solar heating system utilising a phase change material (PCM). Theoretical heat transmission models within spherical capsules containing the PCM were examined. The impact on the overall COP was analysed concerning the volume of the PCM storage tank, melting temperature, collector area, and airflow rate. The simple uniform temperature model is deemed beneficial for long-term system simulations. Sari and Kaygusuz (2002) formulated a eutectic mixture comprising 75.5 wt% lauric acid and 24.5 wt% stearic acid for space heating applications. Eutectic melts were developed at 37°C with a latent heat of 183 kJ/kg, rendering them an appealing phase change material for passive solar space heating applications, including building and greenhouse heating, in relation to climatic circumstances. Vakialtojar (2001) created computational models to assess thermal energy storage systems for space heating and cooling applications. The impact of PCM slab thickness and fluid passage gap on storage performance was examined. He populated the phase change materials ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ and $\text{KF} \cdot 4\text{H}_2\text{O}$) in slender, flat containers, allowing air to circulate through the interstices between them. He determined that the air velocity profile at the entrance does not significantly influence the heat transfer characteristics or the outlet air temperature. Utilising reduced air gaps and thinner PCM slabs can enhance performance; however, this results in an increased quantity of PCM containers and an augmented overall volume of the storage system, consequently leading to a larger pressure drop across the system.

10.3 Refrigeration

The predominant storage medium for space cooling are water, ice, and phase change materials, sometimes referred to as eutectic salts. Phase Change Materials (PCMs) have been utilised for diverse thermal storage applications since the 1800s; nevertheless, their applicability as a medium for space cooling has emerged only recently. Currently, the predominant phase change materials for cool storage are inorganic salt hydrates, organic paraffin waxes, and their combinations. Literature on thermal storage at temperatures below ambient, aside from ice, is few. Solomar et al. (Solomar et al, 1989) reported a theoretical simulation of cool storage. BoHe et al. (2002) examined the feasibility of employing cool storage systems utilising phase change materials, along with a discussion of static and dynamic cool storage processes. The Rubitherm RT5 (melting point 7 °C, latent heat of fusion 158.3 kJ/kg) has been identified as a superior candidate for phase change material (PCM) in cool storage due to its cost-effectiveness, congruent melting behaviour, self-nucleation capability, absence of supercooling, and stability throughout multiple cooling and heating cycles.

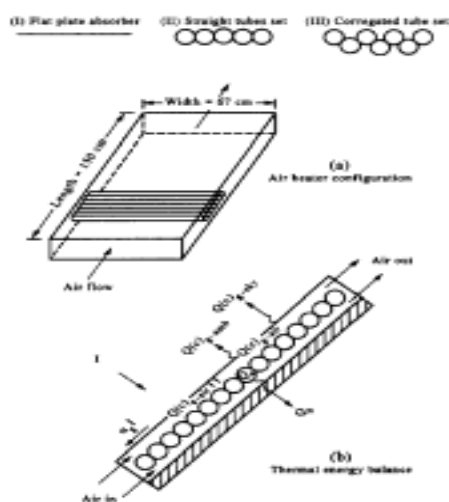


Figure 8. Configuration of a solar air heater with a series of phase change material tubes

A literature review of commercial chemical products related to phase change materials for cool storage within the temperature range of 15 to 23 degrees Celsius was conducted (Kagaku et al, 1998). Nagano et al. (2003) examined the thermal properties of manganese (II) nitrate hexahydrate (melting point 25.8 °C, latent heat of fusion 125.9 kJ/kg) as a phase change material for cooling systems. It was discovered that nearly all chlorides effectively modulated the melting point of $\text{Mn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$. $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ was an excellent additive for modifying the melting point, decreasing supercooling, and reducing the heat of fusion. The temperature differentials necessary for melting and solidification, as determined by differential scanning calorimetry (DSC), are approximately 6 °C for the melting process and 4 °C for the solidification process of the $\text{Mn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ mixture with 4.0 wt% of $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$. Indoor air at 28 °C during the day and external cool air at night below 16 °C can be employed to facilitate the melting and solidification of this mixture. Farid et al. (1998) investigated the viability of cold storage employing dimethyl sulfoxide (melting point 16.5 °C) as a phase change material in a rectangular container. According to the experimental findings and model forecasts, dimethyl sulfoxide can serve as a phase change material for thermal energy storage. The results indicate that the cooling extraction duration is contingent upon the quantity of solidified phase change material (PCM). The cooling extraction phase concluded when the outlet air temperature from the PCM section attained 25°C. This temperature is regarded as the maximum at which humans may experience comfort.

Saitoh and Hirose (1986) conducted an experimental and theoretical investigation of the thermal properties of an encased thermal storage tank. They utilised $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ as a phase change material to fill cylindrical capsules with an internal diameter of 70.7 mm. The primary elements influencing the charging process were determined to be capsule size, coolant flow rate, coolant temperature, and capsule material. Kondepudi et al. (1988) examined the influence of the Biot number, Stefan number, and Fourier number on the thermal efficiency of cold storage. Laybourn (1988) employed a thermal resistance approach that incorporated convective resistance, wall resistance, and ice layer resistance to determine the cold storage capacity of the tank containing rectangular capsules. Arnold (1990) examined heat transport throughout the freezing and melting processes through a series of charging and discharging tests. Chen (1991) formulated a comprehensive lumped model to forecast the thermal efficiency of a cold storage system. The findings indicated that the lump model is an efficient and straightforward approach for assessing the thermal performance of cold storage systems. Ryu et al. (1991) utilised a rectangular storage tank with a copper tube container and performed a series of experiments employing both vertical and horizontal orientations to examine the heat transmission characteristics. Chen (1999) performed a series of experiments to examine the subcooling phenomenon and the freezing probability of water, both with and without nucleation agents, within a cylinder. The incorporation of nucleation agents has been confirmed as an efficient method to enhance the subcooling phenomenon. Chen et al., (2000) conducted an experimental investigation on the pressure drop within an encased thermal storage tank during the charging phase. The cylindrical capsules within the thermal storage tank employ water infused with nucleation agents as the phase change material, while the coolant consists of an aqueous ethylene glycol solution. They determined that elevated cold storage may be achieved by utilising a lower inlet coolant temperature in conjunction with a high flow rate. The heat transfer coefficient rises with an increase in coolant flow rate. The pressure loss across the tank increases as the coolant flow rate rises throughout the charging operation.

10.4 Greenhouse Heating

Solar agricultural greenhouses have been extensively utilised over the past two decades to enhance plant quality and productivity while decreasing fossil fuel demand for heating and cooling. Optimal greenhouses necessitate regulation of temperature, humidity, sun irradiance, and internal gas composition while ensuring efficient energy use. Investigations in this domain, focussing on novel materials, thermal storage, and heat exchange apparatus, have yielded intriguing demonstration units that subsequently led to swift commercial implementations. The

most commonly utilised phase change materials (PCMs) for these applications are $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, polyethylene glycol (PEG), and paraffins.

Nishina and Takakura (1984) conducted research utilising $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ with various additives to inhibit phase separation and degradation for greenhouse heating in Japan. Figure 9 illustrates the overall perspective of the experimental configuration. This study revealed that while the internal objective of 8°C was attained, only 40-60% of the latent heat potential of the PCM was utilised, indicating that nearly half of the PCM was inefficiently employed throughout the energy exchange processes. Takakura et al. (1981) evaluated polyethylene glycol and $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ as phase change materials for greenhouse heating over a ground area of 7.2 m^2 . They contrasted a normal greenhouse with a PCM storage-type greenhouse. The efficiency of the greenhouse, incorporating phase change material (PCM) storage with a solar collector, was 59% and successfully maintained an internal temperature of 8°C during the night, despite an external temperature decrease to -0.6°C . A microcomputer control system has been created to provide enhanced precision and sophistication in the management of solar greenhouse systems.

CNRE-France executed a study employing a glass-covered multi-span greenhouse with a ground area of 500 m^2 , specifically for rose cultivation, utilising 13.5 tonnes of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ (melting at 28°C) as referenced by Jaffrin and Cadier (Chen, 1999) and Jaffrin (1982, 1987). The thermal and agricultural performance of this greenhouse was compared with that of an air-bubble double plastic-covered greenhouse and a regular greenhouse. Figure 10 illustrates the configuration of the PCM containers underground. The containers were positioned on concrete shelves comprising five layers within semi-circular tunnels, utilising air for heat transfer. The study concluded that this technology achieved propane gas savings of 80% and 60% compared to traditional and double-covered greenhouses, respectively. The electricity consumption of the fans was found to be under 10% of the greenhouse's heating demand.

Levav and Zamir (1987) conducted experiments using $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ in a greenhouse setting. The necessary air temperature in the greenhouse was attained without any rise in relative humidity. The primary disadvantage of the technology was emphasised as the $\$1.1/\text{kg}$ expense of the PCM. Moreover, they noted that the 24°C melting temperature of the PCM may be excessive for certain crops.

Kern et al. (1979) employed $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ as a phase change material in aerosol cans to explore energy storage potential within and outside a 36 m^2 greenhouse enveloped in fibreglass. The study's results demonstrated that the external unit released approximately 80-90% of the absorbed energy, but the internal energy release ranged from 60-80%. storage facility. Paraffins have also been utilised for energy storage in greenhouses. A study conducted by Bagetinelik et al. (1994) was the sole publication in the literature utilising paraffin ($48 - 60^\circ\text{C}$, Latent Heat of Fusion 190 kJ/kg) for greenhouse heating.

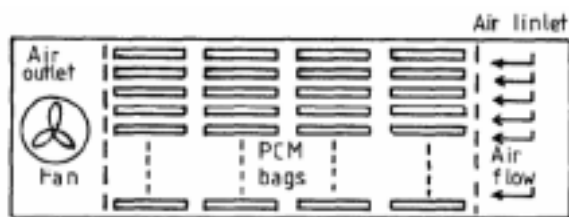


Figure 9. Overview of the phase change energy storage system

The most recent research on $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ -based phase change material applications in greenhouses was conducted by Ktirkliti et al. (1996, 1997). The study utilised two variants of a comparable phase change material (PCM): one with a melting range of $22 - 25^\circ\text{C}$ for mitigating

peak temperatures during summer, and the other with a melting point of approximately 8°C for frost protection in both greenhouses.

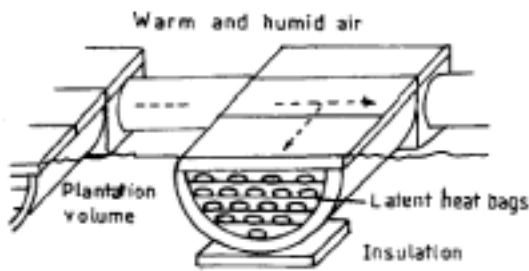


Figure 10. Subterranean tunnel: outfitted with a phase change material

Figure 11 illustrates the experimental configuration for both purposes. Results indicated a temperature differential of around 2.5 - 3°C between the PCM greenhouse and the control greenhouse during the experimental duration, with a solar collecting efficiency of 29% based on external solar radiation for the tests utilising PCM with a higher melting point. The temperature differential and sunlight collection efficiency were approximately 22°C and 30%, respectively, during the frost prevention experiment, successfully preventing frost on 7 out of 9 frosty instances. The majority of applications were conducted in either double-covered greenhouses or greenhouses equipped with one or more layers of thermal screens. The sole study that minimally elucidated the impact of the PCM store on the environmental parameters of a greenhouse appeared to be that of Kuruklu et al. (1996, 1997). All studies indicate that phase change materials (PCMs) can be utilised for both energy storage and humidity regulation in greenhouses, contingent upon the appropriate selection and design of the entire system for optimal energy management.

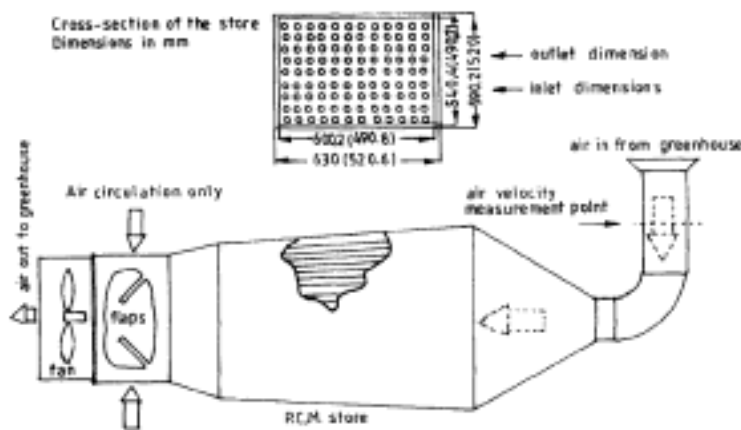


Figure 11. Overview of the storage utilised for energy management within the greenhouse

10.5 Solar Cooking

Solar cookers are utilised for preparing rice, veggies, meat, and baking cakes, among other foods. The comprehensive design, evaluation, theory, and functionality of box-type solar cookers are thoroughly established (Telkes et al, 1959 – Buddhi et al, 2000). The functionality of these cookers is restricted due to the absence of storage, rendering them unusable on overcast days or during the evening hours. The utilisation of phase change materials (PCMs) for latent heat storage has been acknowledged as a promising approach for creating a compact and efficient storage system, owing to its elevated storage density and stable working temperature (Hoda et al, 1977; Garg et al, 1978).

Buddhi and Sahoo (1997) have designed and constructed a box-type solar cooker with latent heat storage tailored for India's diverse climatic circumstances. Commercial-grade stearic acid (melting point 55 °C, latent heat of fusion 161 kJ/kg) utilised as a latent heat storage medium. Figure 12 illustrates the design of a box-type solar cooker intended for a single vessel, using a phase change material (PCM) for solar energy storage. The cooker comprises an aluminum-absorbing tray designated as 'A'. A cylindrical container with a diameter of 0.165 m and a depth of 0.02 m has been welded at the centre of the absorbent plate (shown as 'C' in Fig. 1), designed to securely hold the cooking pot. This container will facilitate heat transfer from the absorbing plate to the phase change material (PCM). Additionally, aluminium fins were installed on the interior surface of the tray and cylindrical container. The outer tray 'B' is constructed from the identical aluminium sheet. The distance between tray 'A' and tray 'B' was maintained at 0.025 m on the lower side. Tray 'B' contained 3.5 kg of commercial-grade Stearic Acid (PCM), ensuring optimal contact between the PCM and the underside of tray 'A'. The gap between tray 'B' and the casing was filled with glass wool to ensure thermal insulation for the bottom and sides of the solar cooker. A flat glass mirror was secured within an aluminium casing.

function as an insulator and a shield for the glass lid when the cooker is not subjected to sun radiation. The exterior of aluminium tray 'A', cooking pot, and its lid were coated with a matte black paint. The experimental findings indicate the viability of employing a phase change material as the store medium in solar cookers, allowing for meal preparation in the evening with a solar cooker equipped with latent heat storage. It also maintains a virtually uniform plate temperature during the late evening.

Domanski et al. (1995) examined the feasibility of cooking during non-sunlight hours utilising phase change materials (PCMs) as storage mediums. The storage-cooking pot was designed for use during non-sunlight hours (Fig. 13). To achieve this, two concentric cylindrical containers, each 0.0015 m thick and constructed from aluminium, are joined at their tops with four screws, creating a double-wall vessel with an interstitial space between the outer and inner walls. The outer vessel has a diameter of 0.18 m, whereas the inner vessel has a diameter of 0.14 m. The annular space between the outer and inner vessels measures 0.02 m. The gap is sealed with a detachable aluminium cover featuring three circular apertures for the insertion of thermocouples and facilitating direct observation during the filling or extraction of the phase change materials (PCMs). An aluminium circular cover serves as the lid for the interior jar.

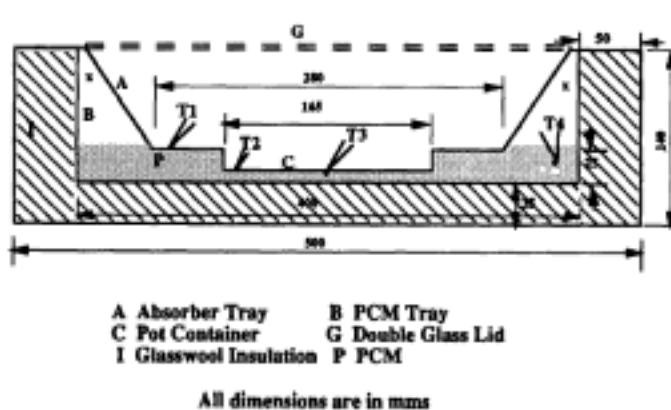


Figure 12. Schematic representation of the solar cooker's box with phase change material storage

The external surfaces of the outer vessel and the coverings are coated with standard black paint to optimise the absorption of solar radiation. The interstice between the outer and inner vessels contains 1.1 kilogramme of stearic acid (69 °C, 95% purity) or 2 kg of magnesium nitrate hexahydrate (89 °C, 99% purity), allowing adequate room for the expansion of the phase change materials upon melting. They determined that the cooker's performance was assessed based on the charging and discharging durations of the PCMs under various settings. He stated that performance is contingent upon solar irradiation, the mass of the cooking medium, and the

thermophysical parameters of the phase change material (PCM). The cooker's overall efficiency when discharging was determined to be 3-4 times superior to that of steam and heat-pipe solar cookers, which are suitable for indoor cooking. In this configuration, the rate of heat transmission from the PCM to the cooking pot during the PCM's discharge is sluggish, necessitating more time for preparing the evening meal.

Sharma et al. (2000) engineered a cylindrical phase change material storage unit for a box-type solar cooker to facilitate food preparation in the late evening. The device encircles the cooking vessel, resulting in an elevated rate of heat transfer between the phase change material and the food, hence facilitating speedier cooking. A PCM container was developed and constructed to accommodate the cooking vessel, as illustrated in the figure. Fourteen. It comprises two hollow concentric aluminium cylinders with diameters of 18 cm and 25 cm, each 8 cm in depth and 2 mm in thickness. The interstitial space between the cylinders was occupied by acetamide (melting point 82 °C, latent heat of fusion 263 kJ/kg) serving as a phase change material (PCM). The pot utilised for cooking measures 17.5 cm in diameter and 10 cm in height, allowing it to fit within the PCM container for culinary applications. To improve the heat transfer rate between the PCM and the inner wall of the PCM container, eight fins (1x3 cm) were affixed to the inner wall of the container. It was observed that utilising 2.0 kg of Acetamide as a latent heat storage medium enables the cooking of the second batch of food if loaded prior to 3:30 P.M. in the winter season. The melting temperature of a PCM is advised to be between 105 and 110 °C for evening cooking. Consequently, it was necessary to select a storage material with an adequate melting point and sufficient quantity to prepare the food in the late evening. To accumulate a greater volume of heat in a phase change material, an increased amount of solar radiation input would be necessary. Consequently, Buddhi and Sharma (2003) employed a latent heat storage unit for a box-type solar cooker including three reflectors. Acetanilide (melting point 118 °C, latent heat of fusion 222 kJ/kg) was utilised as a phase change material for nocturnal cooking. A double-glazed box-type solar cooker, including a 50 cm x 50 cm aperture area and a depth of 19 cm, was employed to perform the cooking trials with the PCM storage unit. This solar cooker features three reflectors, with the central reflector affixed to a hinge allowing rotation solely across the horizontal axis. The remaining two reflectors were secured by a ball-and-socket mechanism on the left and right sides of the reflector. This pair of reflectors possesses three degrees of freedom, allowing movement along the horizontal and vertical axes, as well as rotation about both axes. Through these methods, attempts were undertaken to maintain the reflected solar irradiance on the absorber surface to augment the incident solar radiation on the glass cover during the sunlight exposure trials.

In accordance with Sharma et al. (2000), a cooking apparatus incorporating latent heat storage was built and constructed for nocturnal or late evening food preparation. The unit has two hollow concentric aluminium cylinders with diameters of 20 cm and 30 cm, each 12.5 cm in depth and 2 mm in thickness. The interval between the cylinders was occupied with 4.0 kg of phase change material to facilitate the cooking trials with all three reflectors. The pot utilised for cooking measures 19 cm in diameter and 15 cm in height, allowing it to fit within the PCM storage unit for culinary applications. To improve the heat transfer rate between the PCM and the inner wall of the PCM container, eight fins (1 cm x 3 cm) were affixed to the inner wall of the container. The experimental results indicate that the cooking trials were effectively executed until 8 P.M. use 4.0 kg of phase change material during the winter season in India.

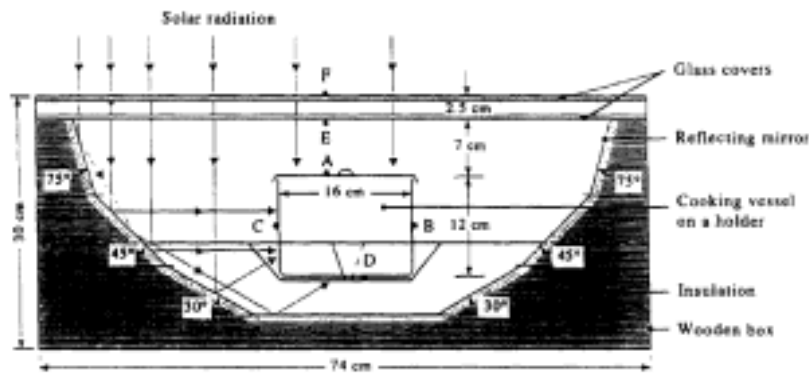


Figure 13. Solar Cooker Featuring a Phase Change Material Cooking Container

Sharma et al. (2004) devised a solar cooker utilising an Evacuated Tube Solar Collector (ETSC) with phase change material (PCM) storage, as seen in Fig. Fifteen. The system comprises an ETSC, a closed-loop pumping line carrying water as the Heat Transfer Fluid (HTF), a phase change material (PCM) storage unit, a cooking unit, a pump, a relief valve, a flow meter and a stainless steel tubing heat exchanger. The PCM storage unit comprises two hollow concentric aluminium cylinders, with inner and outer diameters of 304 mm and 441 mm, respectively, and a depth of 420 mm, featuring a thickness of 9 mm (Fig. 16). The interstice between the cylinders was occupied by 45 kg of erythritol (melting point 118 °C, latent heat of fusion 339.8 kJ/kg), utilised as the phase change material (PCM). A pump sends the heated water (HTF) from the ETSC through insulated pipes to the PCM storage unit via a stainless steel tubing heat exchanger that encircles the cooking unit in a closed loop. During daylight hours, warm water transfers its thermal energy to the PCM and is stored as latent heat via a stainless steel tube heat exchanger. The stored heat is employed to prepare food throughout the evening or when solar intensity is inadequate for cooking. They determined that cooking occurred twice daily, at midday and in the evening. Midday cooking did not influence evening cooking, and evening cooking utilising PCM storage was determined to be more efficient than midday cooking. Experiments and analyses demonstrated that the prototype solar cooker exhibited good performance despite suboptimal heat transmission; the revised design of the heat exchanger in the thermal storage unit will improve the heat transfer rate in the current configuration.

10.6 Phase Change Material

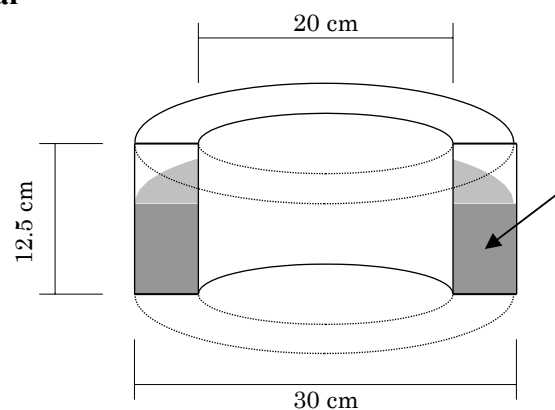


Figure 14. A schematic representation of the latent heat storage unit

Ramadan et al. (1987) developed a basic flat-plate solar cooker incorporating focussing plane mirrors and energy storage materials. The incorporation of a half-centimeter thick sand jacket surrounding the cooking pot has significantly enhanced the performance of the cooker. They determined that a cooking duration of six hours per day has been documented. Approximately three hours of indoor cooking each day has been accomplished. An overall energy conversion efficiency of up to 28.4% has been achieved. The feasibility of employing a PCM as a storage

media to achieve extended cooking durations was examined. A thin layer of the salt hydrate $\text{Ba}(\text{OH})_2 \cdot 8\text{H}_2\text{O}$ was proposed as a jacket surrounding the cooking kettle. Bushnell (1988) introduced a prototype for solar ovens utilising pentacrythritol as a solid-solid phase change material (PCM). He delineated the performance through efficiency assessment and the establishment of a figure of merit.

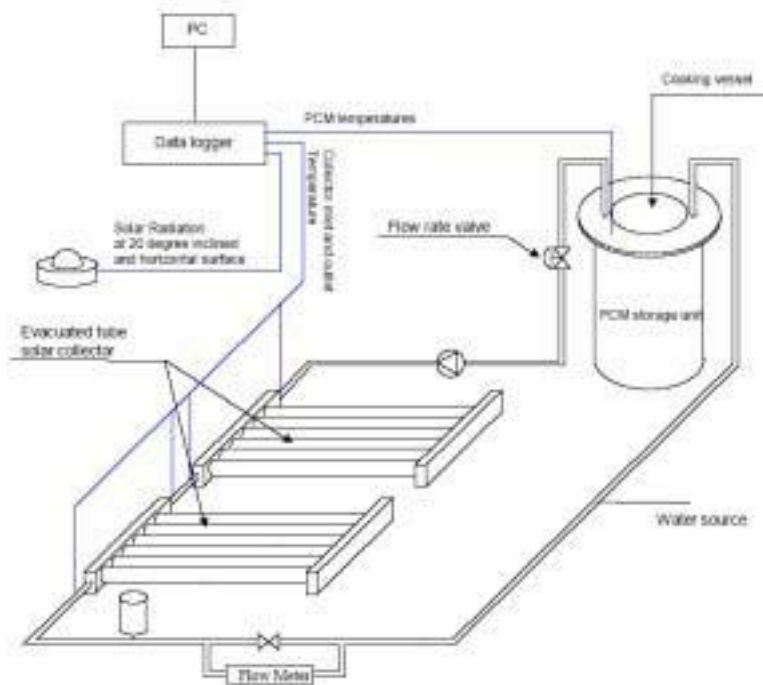


Figure15. Outline of the prototype solar cooker based on evacuated tube solar collector with PCM storage unit

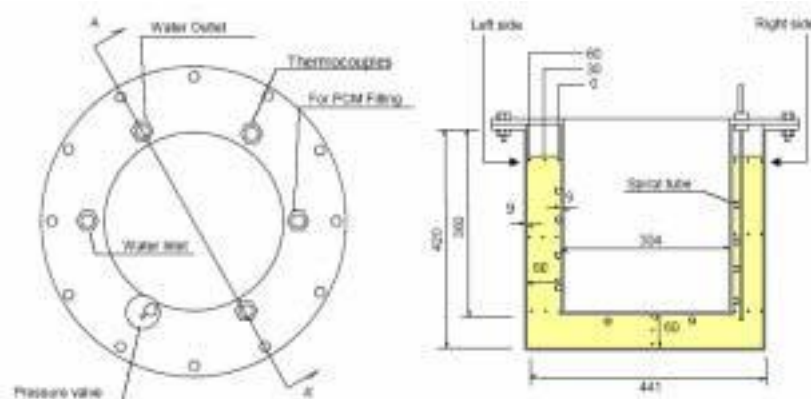


Figure. 16 (a). Sectional view of the PCM storage unit. **Figure. 16(b).** Vertical perspective of the PCM storage device

10.7 Waste Heat Recovery Systems

The air conditioning system expels both sensible and latent heat, with sensible heat comprising approximately 15-20% of the total heat discharged. The compressor's elevated temperature is rather high ($< 65\text{ }^{\circ}\text{C}$) while utilising Freon as a refrigerant. Consequently, it can be recuperated via an accumulator, resulting in elevated thermal energy. Zu et al. (2004) devised a heat recovery system utilising phase change materials (PCM) to reclaim the expelled heat from air conditioning systems, thereby generating low-temperature hot water for washing and bathing purposes. The study determined that the heat recovery system reduces both the primary energy consumption for

heating residential hot water and the heat dissipation to the environment resulting from air conditioning systems. The efficiency ratio of the system significantly improves when all rejected sensible and latent heat from air conditioning systems is recovered. The technical grade paraffin wax and its mixes with liquid paraffin and lauric acid are suitable as phase change materials for heat recovery in air conditioning systems.

An efficient application of urban waste heat from co-generation systems, generally accessible at temperatures ranging from 60 to 100 °C. Kakiuchi et al. have examined erythritol (melting point 118 °C; latent heat of fusion 339.8 kJ/kg) (Ona et al, 2001, Kakiuchi et al, 1998), which is applicable in high-temperature industrial waste heat processes. A multitude of investigations has been conducted on stearic acid (Buddhi et al, 1999, Sari et al, 2001). This material possesses a melting point ranging from 60 to 70 degrees Celsius and is costly. Its utility in waste heat systems is restricted. Nagano et al. (2004) offered a combination of $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ as the primary material, with $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ as an addition to adjust the melting point. It was claimed that the incorporation of 5-10 wt% of $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ can solidify $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (melting point 80 °C, latent heat of fusion 150 kJ/kg). Augmenting the mix ratio had minimal impact on the heat of fusion, although facilitated a reduction in the melting point to approximately 60 °C. No deterioration in the melting point or latent heat of fusion was noted during 1000 accelerated thermal cycles. Yagi et al. (1995) performed foundational research on heat transfer to design a latent heat storage technology for recovering high-temperature waste heat above 500 K. Experiments on heat transfer were conducted for both a single encapsulated phase transition material and a packed bed. The metallic phase change materials demonstrated exceptional efficacy in thermal storage due to their uniform temperature distribution within the capsule. Simulation results indicate that concurrent flow for heat storage and release demonstrates superior efficacy in utilising stored heat compared to counter-current flow.

Buddhi (1997), engineered and constructed a shell and tube heat exchanger for low-temperature waste heat recovery, utilising stearic acid (melting point 59 °C, latent heat of fusion 198 kJ/kg) as a phase transition material for this investigation. The thermal performance of this system was assessed during the charging and discharging processes of the phase change material at various mass flow rates. The schematic diagram of the shell and tube heat exchanger is illustrated in the figure. Seventeen. The utilised phase change material exhibits inadequate thermal conductivity; hence, to improve the system's effective thermal conductivity, the radial spacing between the tubes was maintained at 3 to 4 centimetres. The shell included 50 kg of commercial-grade stearic acid utilised as a latent heat storage medium. The energy-charging test commenced with the circulation of hot water through the HTF tubes, followed by the extraction of stored energy via the introduction of cold water into the HTF tubes. The ambient temperature, flow rate, and phase change material temperatures of the heat exchanger were concurrently recorded at 15-minute intervals. He determined that the experimental findings demonstrate the viability of employing PCM as storage material in heat recovery systems. The suboptimal thermal conductivity of the PCM results in a low total heat transfer coefficient, necessitating the incorporation of fins to enhance the efficiency of the heat exchanger. The spacing between tubes, fins, and mass flow rates must be meticulously chosen to enhance the efficiency of the heat exchanger. Paraffin wax (melting point 54 °C, latent heat of fusion 184 kJ/kg) was utilised in a shell and tube heat exchanger for waste heat recovery (Buddhi et al, 2003). Fins were utilised for efficient heat transfer.

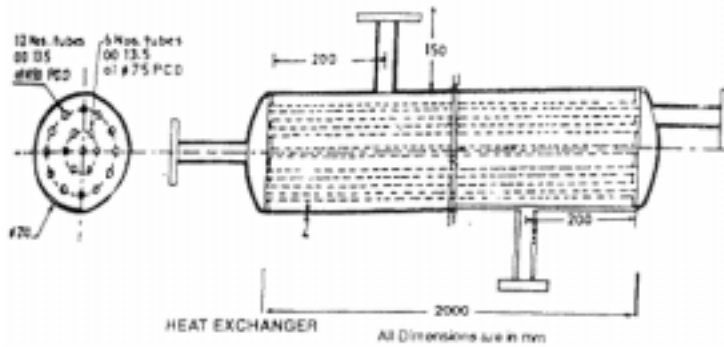


Figure 17. Shell-and-tube heat exchanger using latent heat storage material

11. LATENT HEAT STORAGE EXCHANGER

Latent heat storage systems primarily rely on the examination of heat storage materials and the advancement of heat exchangers that ensure a high effective heat transfer rate for rapid charging and discharging. A heat exchanger utilising high-temperature phase change materials not only possesses a significant capacity for thermal energy storage but also enhances the applicability of the stored energy. Achieving an adequate rate of heat transfer from latent thermal energy storage devices is consistently problematic due to suboptimal heat exchanger design. Various types of heat exchangers have been developed to address this deficiency. A double pipe heat exchanger for latent thermal energy storage has been examined (Fath et al, 1991). This research indicated that the heat transfer rate can be improved by elevating the air inlet temperature, augmenting the air mass flow velocity, and extending the heat exchanger length. A single full-length heat exchanger demonstrated superior thermal effectiveness compared to two half-length parallel heat exchangers of identical capacity. A direct contact heat exchanger utilising an immiscible heat transfer fluid within the phase change material (PCM) has removed the permanent heat exchange surface and has been validated to inhibit phase separation of the PCM (Farid et al, 1989 – Sokolov et al, 1991).

Classical double-pipe or shell-and-tube heat exchangers have been utilised in energy storage systems, with theoretical and experimental analyses of the phase-change phenomenon limited to the geometry of cylindrical capsules, annular gaps, and spherical or rectangular enclosures. A alternative design incorporates three varieties of phase change materials (PCMs) with distinct melting temperatures (Watame). This facilitates optimal utilisation of the HTF energy. The utilisation of plate heat exchangers was considered to offer a more efficient and compact heat exchange design (Bansal et al, 1992). Erk and Dudukovic (1996) introduced an innovative energy storage technology of n-octadecane held by capillary forces within a porous silica substrate. This arrangement removes the costly heat exchange surface, enhances energy density, and increases the rates of energy storage and release. Lecomte et al. (1985) proposed a design methodology for determining the dimensions of a shell-and-tube latent heat exchanger inside a thermal system under specified thermodynamic parameters. They determined that elevated flow rates were incapable of transferring much heat from the PCM to the load. The transfer of heat from the phase change material (PCM) to the load is contingent upon the efficacy of the heat exchanger and the thermophysical characteristics of the PCM. Bathelt (1980) investigated the thermal transfer throughout the melting process from a horizontal cylindrical heat source exhibiting a homogeneous surface heat flow and temperature, utilising a fluid circulated via a multipass heat exchanger immersed in n-heptadecane and n-octadecane. The instantaneous configuration of the melt volume was documented photographically, and local heat transfer coefficients at the solid-liquid interface were ascertained. In quasi-steady melting, the local and average heat transport is connected in a dimensionless manner. The correlation was utilised to compute the position of the solid-liquid interface, which aligned well with the experimental data.

Saxena et al. (1982) introduced a basic model for calculating potential thermal energy storage in shell and tube heat exchangers. The impact of numerous parameters, including the thermal and physical properties of phase change materials (PCM) and convective fluids, heat exchanger size, and flow rates of heat transfer fluids in both laminar and turbulent regimes on energy storage durations is examined. El - Kassaby et al. (1993) modelled the performance of a low-temperature phase transition material in a heat exchanger for short-term storage. A superior correlation was achieved for the outlet air temperature in comparison to the experimental observations, with discrepancies not surpassing 0.5°C throughout the simulated duration. This simulation method is applicable to any phase change material (PCM) with established thermophysical parameters and can forecast the transient movement of the freezing or melting front, as well as the mass fraction of either the liquid or solid phase relative to the total PCM mass.

Kamimoto et al. (1986) designed a latent heat thermal storage exchanger utilising form-stable high-density polyethylene. In their design, the hot fluid entered the exchanger from the top during the charging operation, while the cold fluid entered from the bottom during the discharging process. No rationale was provided for the adoption of this operational style. Bellecci et al. (1993) conducted numerical simulations of the cyclic thermal processes in a shell-and-tube latent heat thermal storage exchanger. The design incorporated the introduction of hot and cold fluids from the same end of the storage exchanger during the sequential charge and discharge operations. Gong et al. (1994) sought to determine which operational method is superior between Kamimoto (1986) and Bellecci et al. (1993). A finite element model was created to simulate the cyclic thermal process in a shell-and-tube latent heat thermal storage exchanger. This exchanger has a tube encircled by an exterior coaxial cylinder constructed from a phase change material (PCM). A heat-transfer fluid circulates through the tube to either store or remove thermal energy from the phase change material (PCM). Numerical investigations demonstrated that entering the hot and cold fluids from the same end of the storage exchanger is preferable to introducing them from opposite ends. The numerical findings also offer help for selecting the proper mode. The results are confined solely to conduction-controlled melting and freezing heat transfer in the phase change material (PCM).

Hasan (1994) created a straightforward tube-in-tube heat exchanger for thermal energy storage utilising stearic acid as a phase change material (PCM). He discovered that the melting front progresses radially inward and axially downward within the PCM tube. The velocity of the melting front was accelerated by a convection heat transfer mechanism within the melted phase change material (PCM). Phase transition can be expedited by positioning the heat exchanger horizontally instead of vertically. He et al. (2001) conducted a theoretical study and experimental evaluations of an innovative shell-and-tube latent heat exchanger, establishing a foundation for its optimal design and operation. They indicated that some parameters, including inlet temperature, fluid velocity, PCM thickness, and flow channel length, significantly influence the heat transfer performance of the unit. Consistent heat output can be achieved by elevating the inlet temperature of the heat transfer fluid, increasing the thickness of the phase change material, and extending the flow channel length. Banaszek et al. (1999) employed a spiral heat exchanger within a latent heat storage unit. The system's most attractive qualities include compactness, improved heat transfer from centrifugal forces, ease of sealing, an extensive heat transfer surface, and a reduced undisturbed flow length. Qarnia et al. (2001) introduced a mathematical model to simulate the thermal dynamics of a cross-flow heat exchanger, using layers of phase change material (PCM) positioned between the hot and cold air streams to mitigate icing. The mathematical model was corroborated using empirical data. Thermal resistance was shown to impact exchanger performance by diminishing the dimensionless output temperature of the cold air stream.

12.0 MEASUREMENT METHODOLOGIES FOR THERMO-PHYSICAL PROPERTIES

The various measuring techniques currently employed for determining the latent heat of fusion and melting temperature of phase change materials (PCMs) can be categorised as follows: (i) Drop Calorimeter (DC), (ii) Differential Thermal Analysis (DTA), and (iii) Differential Scanning Calorimeter (DSC). The DC approach necessitates considerable time investment, and the precision of the outcomes is suboptimal (Buddhi et al, 1987). In DSC and DTA procedures, sample and reference materials are subjected to heating at a consistent pace. The temperature differential between the two materials is directly proportional to the disparity in heat flow, and this record is referred to as the DSC curve. The suggested reference material is Alumina (Al_2O_3). The latent heat of fusion is determined by the area beneath the peak, whereas the melting temperature is assessed by the tangent at the point of maximum slope on the peak's face. A multitude of researchers have employed Differential Scanning Calorimetry (DSC) to assess the thermophysical properties of Phase Change Materials (PCMs) (Flaherty, 1971; Giavarini et al., 1972; Cantor et al., 1978; Elder et al., 1980; Salyer et al., 1986; Bukovec N. et al., 1989; Dunn J.G. et al., 1989; Aboul-Enein et al., 1991; Takahashi Y. et al., 1991; Babich M.W. et al., 1992; Richardson M.J. et al., 1993; Gibbs et al., 1986; Feldman D. et al., 1996; Li W. et al., 1999; Sharma S.D. et al., 1999; Sharma, A. et al., 2002; Liu et al., 2001) (Flaherty et al, 1971 – Liu et al, 2001).

The aforementioned methods are generally regarded as precise for determining the heat of fusion. The thermophysical properties of a minimal quantity (1-10 mg) of the sample phase change material may differ from those of the bulk components, including heterogeneous additions. Zhang developed a T-history approach as an alternative for ascertaining the thermophysical characteristics of PCM, aimed at overcoming the aforementioned limitations of DSC. This method's requirement for a minimal sample volume renders it highly suitable for conducting cycle tests using sealed tubes holding newly developed phase change materials (PCMs). Nonetheless, the original T-history technique is constrained in its accuracy of thermophysical parameters due to the incorporation of some erroneous physical assumptions. Hong et al. (2004) endeavoured to enhance the precision of the T-history approach for quantifying the heat of fusion of diverse materials. Marin et al. (2003) enhanced the methodology of Zhang et al. to ascertain temperature-dependent characteristics. Their analysis indicates that this method facilitates the straightforward acquisition of both characteristics and curves, significantly aiding in the selection of heat storage materials and the subsequent design of thermal energy storage systems. The enthalpy–temperature curves facilitate the acquisition of average material properties by allowing the assessment of thermal property variations with temperature.

12. THERMAL CYCLES

For latent heat storage, commercially available phase change materials (PCMs) with around 95% purity are favoured due to their widespread availability and cost-effectiveness. The thermophysical characteristics and behaviour of commercial-grade materials significantly differ from those reported in the literature for laboratory-grade materials (purity exceeding 99%). Given the scarcity of data about the impact of thermal cycling on commercial-grade phase change materials (PCMs), it is crucial to investigate its impacts on melting temperature, latent heat of fusion, and specific heat of these materials. Sharma et al. (1998, 2002) performed accelerated heat cycle testing on stearic acid, acetamide, and paraffin wax. They determined that commercial-grade phase change materials exhibit no consistent decrease in their melting points after undergoing 1500 heat cycles. Acetamide and paraffin wax exhibit commendable stability during the cycle process and may be regarded as promising phase change materials (PCMs). It is advisable to undertake a heat cycle test on commercial-grade materials intended for use as PCM, as their behaviour may vary. Ting et al. (1987) performed accelerated cycle testing on a phase change material (PCM) unit containing $\text{Na}_2\text{SO}_4 \cdot n\text{H}_2\text{O}$ at various weight ratios. The researchers examined the impact of 1000 temperature cycles on the container tube, although did not assess

its influence on the thermophysical properties of the PCM. Fernanda (1988) has investigated the thermal reliability of salt hydrate phase change materials (PCMs) with melting temperatures ranging from 15 to 32°C by assessing latent heat of fusion and melting temperature during repeated cycles.

Sharma et al. (2001) examined the impact of thermal cycling on urea and observed that it did not undergo melting after multiple cycles. It was recommended that urea not be utilised as a phase change material (PCM). Hadjieva (1992) computed the enthalpy of three paraffin mixtures, revealing its dependency on oil content and atomic distribution as determined by chemical and gas chromatographic investigations. Thermal cycle testing was conducted on a mixture of technical grade paraffins, which demonstrated stability after undergoing 900 heating and cooling cycles. Gibbs (1995) indicated that paraffin exhibits exceptional heat stability. Kimura and Kai (1984) utilised NaCl to enhance the stability of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, which had a somewhat more amount of water than the stoichiometric ratio. The salt demonstrated exceptional stability after undergoing over 1000 heating and cooling cycles. Porisino (1988) investigated the thermal reliability of salt hydrate phase change materials (PCMs) by assessing the latent heat of fusion and melting temperature during repeated cycles. Wada et al. (1984) examined the diminishing heat storage capacity of $\text{CH}_3\text{COONa} \cdot 3\text{H}_2\text{O}$ during thermal cycling and conducted calorimetric assessments on three distinct sample types. Hasan and Sayigh (1994) examined the thermal characteristics of certain saturated fatty acids utilising the DSC technique during a medium-term duration that encompasses

Heating and cooling cycles totalling 450 occurrences. The thermal energy storage capability of $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ was examined. concerning heat cycling as discussed by Marks (1980). Zhang et al. (2001) investigated the solid-liquid phase transitions in lauric, palmitic, and stearic acids, together with their binary systems. They also examined the durability of the thermal properties over multiple heating-cooling cycles, specifically 30, 50, 80, and 100 cycles. Sari (2003, 2003) performed 1200 accelerated thermal cycle tests to investigate the thermal reliability of lauric, myristic, palmitic, and stearic acids. Thermal cycling studies have been performed on wallboards impregnated with 24 wt% PCM. The samples exhibited no propensity for the PCM (paraffin) to migrate within the wallboard, and there was no discernible degradation in the thermal energy storage capacity (Khudhair 2003).

13. DETERIORATION OF THE PHASE CHANGE MATERIALS

Porosini (1988) and Groll et al. (1990) evaluated the corrosion of various salt hydrates and salt eutectics on different container materials, as well as their thermal stability. Recently, Cabeza et al. (2001 - 2001) investigated the corrosion resistance of five prevalent metals (aluminium, brass, copper, steel, and stainless steel) when exposed to molten salt hydrates (zinc nitrate hexahydrate, sodium hydrogen phosphate dodecahydrate, calcium chloride hexahydrate, sodium carbonate, potassium hydrogen carbonate, potassium chloride, water, sodium acetate trihydrate, and sodium thiosulphate pentahydrate) in an immersion corrosion test. Recently, Sari et al. (2003) examined the corrosion resistance of various construction materials to fatty acids (stearic, palmitic, myristic, and lauric acid) for an extended duration. The materials used for the containers were stainless steel (SS 304 L), carbon steel (C₂₀), aluminium (Al), and copper (Cu). It can be concluded that stainless steel (SS304L) with a chromium oxide (Cr_2O_3) surface layer and aluminium (Al) with an aluminium oxide (Al_2O_3) surface layer are fundamentally compatible with the examined fatty acids, as evidenced by gravimetric and metallographic corrosion test findings. Carbon steel (Steel C₂₀) and copper (Cu) are preferentially compatible materials for storage containers.

14.0 ENHANCEMENT OF HEAT TRANSFER

In a latent heat storage system, the solid-liquid contact recedes from the heat transfer surface during the phase transition. Throughout this process, the surface heat flux diminishes as a result of the escalating thermal resistance associated with the increasing thickness of the

molten/solidified layer. During solidification, conduction serves as the sole transport mechanism, which is often inefficient. During melting, natural convection may arise in the molten layer, typically enhancing the heat transfer rate relative to the solidification process, provided the layer is sufficiently thick to facilitate natural convection. Nevertheless, the typically poor heat transfer rate can be significantly improved with the application of an appropriate heat transfer augmentation technology. Numerous techniques exist to improve heat transfer in an LHTS system. Various researchers have recommended the utilisation of finned tubes with diverse configurations as an effective method to enhance the charge/discharge capacity of an LHTS system (Velraj et al,1997 – Baner et al, 2000). Additional techniques for enhancing heat transfer in latent heat thermal storage (LHTS) systems include the incorporation of phase change materials (PCM) within a metal matrix, the dispersion of PCM with high-conductivity particles, microencapsulation of PCM, the use of an embedded graphite matrix, carbon fibre brushes exhibiting high thermal conductivity (190 W/mK), exfoliated graphite to enhance the thermal conductivity of form-stable P/HDPE composite PCMs, the insertion of copper plates within spherical capsules containing n-octadecane PCM, and the utilisation of metal screens or spheres positioned inside the PCM. Erik and Dudukovic (1996) introduced an innovative energy storage technology including n-octadecane maintained by capillary forces within a porous silica substrate. This arrangement removes the costly heat exchange surface, enhances energy density, and increases the rates of energy storage and release. Leoni and Amon (1996) utilised aluminium foam to improve the heat transmission mechanism in a latent heat storage system.

15. NOVEL PCM INNOVATIONS

Ravankar (2001) introduced an innovative testing methodology for satellite power utilising latent heat storage. PCM transitions to a liquid state at elevated temperatures, thereafter solidifying during prolonged periods of cold darkness and releasing its latent heat. The emitted heat can be utilised to produce electricity by powering thermoelectric equipment. John et al. (2000) developed an innovative nighttime cooling ventilation system, integrating phase change materials and heat pipes as an alternative to air conditioning. The technology provides significant advantages by diminishing or eradicating the necessity for air conditioning. Microencapsulated phase change materials can be integrated into textile fibres, composites, and garments to significantly improve thermal insulation in both hot and cold conditions (Colvin et al, 1998). Cabeza et al. (2002) indicated that phase change materials (PCMs) are effective for delivering temperature-sensitive drugs and food due to their capacity to store heat and cold within a range of several degrees. Numerous firms are involved in the investigation of transporting temperature-sensitive phase change materials for diverse purposes (201 - 205).

Vasiliev et al. (2000) devised a latent heat storage module for motor vehicles, enabling heat retention when the engine is off, which may then be utilised to preheat the engine upon restart. Utilising heat storage enables the engine to attain an optimised operating temperature in a significantly reduced timeframe compared to the absence of heat storage. Pal and Joshi (1996, 1997) advocated for the use of PCM to limit the maximum temperature of electronic components. Tan et al. (2004) performed an experimental investigation on the thermal management of mobile electronic devices and computers, utilising a heat storage unit (HSU) containing n-eicosane as the phase change material (PCM) within the device. The elevated latent heat of n-eicosane in the HSU absorbs heat dissipation from the chips, sustaining the chip temperature below the permissible service temperature of 50 °C for 2 hours during transient operations of the PDA.

Climator (Ulfvengren et al, 2004) has created a cooling vest for athletes to lower body temperature. Phase Change Materials (PCMs) have also been suggested for the cooling of newborns (Olsson et al, 2004). Koschenz et al. (2004) devised a thermally activated ceiling panel for integration into lightweight and retrofitting structures. Simulation studies and laboratory testing indicated that a 5 cm layer of microencapsulated phase change material (25% by weight) and gypsum can maintain a pleasant room temperature in ordinary office buildings. Heptadecane was tested as a phase change material in this prototype configuration. Naim et al. (2002)

developed an innovative continuous single-stage solar still incorporating phase change material (PCM). The productivity of a solar still can be significantly improved through the integration of a phase change material (PCM) with the still. Huang et al. (2004) employed phase change materials for the thermal regulation of building-integrated photovoltaics. Under varying ambient conditions, a PV/PCM system may facilitate the photovoltaic module's operation close to its optimal temperature of 25°C. They created a PV/PCM simulation model and validated it against experimental results. The enhancement in thermal performance attained through the utilisation of metal fins in the PCM container is substantial. The fins facilitate a more consistent temperature distribution inside the PV/PCM system. A comprehensive experimental investigation has been conducted on the thermal properties of a phase change material utilised to regulate the temperature increase of photovoltaic systems in a PV/PCM configuration (Huang et al, 2001- Huang et al, 2002). Tavaranan et al. (2002) proposed the utilisation of phase change materials (PCM) in conjunction with solar (PV) panels and thermoelectric modules (TEMs) for the creation of a portable vaccination refrigerator intended for distant settlements lacking grid electricity. Thermoelectric modules (TEMs), which convert electrical energy into thermal energy through the Peltier effect, serve as effective alternatives for eco-friendly cooling applications, particularly for modest cooling demands and when compactness is essential. Omer et al. (2001) have conducted experimental investigations on thermoelectric refrigeration systems utilising latent heat storage. Duffy and Trelles (2003) proposed a numerical simulation of a porous latent heat thermal energy storage system for thermoelectric cooling, examining various porosities of the aluminium matrix. A porous aluminium matrix was employed to enhance system performance by boosting heat conduction while minimally impacting stored energy.

Weinlader et al. (2004) employed phase change materials in double-glazed façade panels for daylighting and thermal regulation. A façade panel using PCM exhibits around 30% reduced heat loss in south-facing facades. Solar heat gains are diminished by around 50%. Facade panels with phase change materials significantly enhance thermal comfort in winter, particularly during the nighttime hours. During summer, these systems exhibit minimal heat gains, hence diminishing peak cooling demands throughout the day. Evening heat gains can be mitigated with overnight ventilation. Utilising a phase change material (PCM) with a low melting point of up to 30°C will enhance thermal comfort during the day in summer, in contrast to double glazing without or with internal sun protection. Ying et al. (2004) established the testing requirements for PCM fabrics. Three indices have been suggested to define the thermal functional performance of PCM textiles. The index of thermal regulation capability describes the thermal performance of PCM fabrics and is significantly influenced by the quantity of PCM present. Khateeb et al. (2004) developed a lithium-ion battery utilising an innovative phase change material (PCM) for the thermal management system in electric scooters. A developed Li-ion battery was proposed to substitute the current lead-acid battery in the electric scooter, without necessitating any mechanical modifications to the battery compartment.

16. CONCLUSION AND FUTURE PERSPECTIVES

Elevated intake temperatures and increased flow rates of heat transfer fluid systems are necessary for the optimal operation of thermal energy storage (TES). The retrieval time and energy storage capacity are substantial for a system combining Sensible Heat Storage (SHS) and Latent Heat Storage (LHS). Therefore, the implementation of a combined SHS and LHS system is advised. Minimal changes are seen between the use of paraffin and stearic acid as phase change materials during charging and discharging procedures. Nevertheless, variations in latent heat and thermal conductivity demonstrate that paraffin's performance is marginally superior (5-7%). Both PCMs are appropriate for thermal energy storage systems.

The notable benefits of Thermal Energy Storage (TES) systems encompass minimal energy loss during storage, elevated energy densities, and the potential for more compact configurations. Further research is essential to augment the understanding of the engineering and scientific attributes of thermochemical TES systems. The efficacy and execution of these systems can only

be assessed and enhanced through the conduction of such research. Thermochemical materials constitute a crucial element of these systems. The selection of thermochemical materials is influenced by their availability, cost, durability, energy density, degradation, and cyclic behaviour. Additional research is necessary for design elements, safety, dimensions, efficiency, maintenance, economics, and installation. A comprehensive analysis of these systems should be conducted, emphasising the energy and exergy requirements. Such evaluations can facilitate the optimisation and enhancement of design. Numerous endeavours are underway in this domain, and it is anticipated that they will provide significant new discoveries and experimental outcomes.

This review will assist in identifying appropriate phase change materials (PCMs) for diverse applications, various methodologies for measuring the thermophysical properties of PCMs, suitable heat exchangers with strategies to enhance heat transfer, and various designs for heat storage utilising PCMs across applications such as heating, cooling, cooking, greenhouse management, water heating, and waste heat recovery systems. The study examines temperature cycles and corrosion of materials for long-term stability. Recent advancements in PCM applications are highlighted to enhance awareness of novel uses. Additional applications remain to be identified.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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MODELLING MGO-DRIVEN QUICKLIME REACTIVITY TO REDUCE ENERGY CONSUMPTION IN OBAJANA LIMESTONE CALCINATION

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ABSTRACT

Lime production ranks among the most energy-intensive industrial processes, with calcination and slaking driving substantial fuel use and CO₂ emissions. This study addresses the gap in quantifying how magnesium-oxide (MgO) content in Obajana limestone (Nigeria) governs quicklime reactivity and associated energy demand. We collected ten limestone samples at 10 m intervals, ground them to 250 µm and 450 µm, determined chemical composition via X-ray fluorescence, and calcined at 901 °C for 60 min. Slaking reactivity ((R), °C s⁻¹) was measured per ASTM C110.12, and five regression forms (linear, logarithmic, exponential, power, polynomial) were fitted in R 4.0.5. A second-order polynomial model best explained reactivity variance (R² = 0.948 for 250 µm; R² = 0.957 for 450 µm). Reactivity declined by 85 %–98 % as MgO rose from 0.0982 % to 0.8336 %, implying that sourcing limestone with MgO < 0.3 % and 250 µm feed size can reduce slaking-energy consumption by over 80 %. These first-of-its-kind empirical findings furnish practical guidelines for energy-efficient limestone selection and process planning in Nigeria's lime industry, advancing SDG 7 on affordable and clean industrial energy.

1. INTRODUCTION

Lime manufacture ranks among the most energy-intensive industrial processes, often accounting for up to 8 percent of process heat demand and significant CO₂ emissions in the cement and lime sector (Siebert et al., 2018). Nigeria possesses abundant limestone reserves and a pressing need to diversify its energy and industrial base through more efficient mineral-processing routes (Giwa, 2025). In quicklime production, the reaction of calcium oxide (CaO) with water, known as slaking, releases heat rapidly and depends critically on CaO particle properties shaped during calcination; magnesium-oxide (MgO) content in the original

limestone influences these properties and thus energy requirements for slaking (Giwa, 2025, Ch. 1, pp. 2–3).

However, no studies to date have empirically modelled how MgO content in Obajana limestone affects quicklime reactivity or quantified the associated energy savings. This study develops and validates an empirical model linking MgO composition to quicklime reactivity and estimates potential reductions in calcination and slaking energy. The findings deliver the first data-driven guidelines for selecting limestone grades that enhance lime-kiln energy efficiency in Nigeria's burgeoning mineral sector.

2. LITERATURE REVIEW

2.1 Thematic Review

2.1.1 Energy Intensity of Lime Manufacture

Lime production consumes up to 8 % of all industrial process heat, largely in calcination (900–1200 °C) and slaking, leading to significant CO₂ emissions (Siebert et al., 2018). In Nigeria, operational inefficiencies in vertical-kiln and rotary-kiln systems can raise fuel use by 15–20 % (Okoro & Nwankwo, 2020). Quantifying reactivity-driven energy savings remains unexplored in this context.

2.1.2 MgO Influence on Quicklime Structure and Reactivity

Trace MgO alters CaO crystal growth during calcination, enlarging crystallites and reducing pore volume—thus diminishing quicklime reactivity (Feng et al., 2019). Calorimetric studies report a 12 % increase in slaking enthalpy when MgO > 0.5 % (Awan and Khan, 2019), yet no kinetic or energy models integrate MgO content as a predictor variable.

2.1.3 Slaking Kinetics and Energy Release

Slaking—a hydration reaction of CaO to Ca(OH)₂—releases ~490 Btu/lb of CaO (Byun & Yoon, 2016). Kinetic models show that impurities retard rate constants (k), but existing work focuses on SiO₂ rather than MgO. A kinetic framework specific to MgO-driven rate changes and associated heat-utilisation efficiency is lacking.

2.1.4 Empirical and RSM Approaches in Mineral Processing

Response-surface methodology (RSM), particularly Box–Behnken designs, has optimised feed parameters to reduce energy in mineral calcination and disintegration (Delgado & Chica, 2017; Zhang et al., 2022). Yet, no studies apply RSM or regression modelling to correlate MgO content with quicklime reactivity and slaking energy.

2.2 Gap

Despite advances in kiln-energy audits, microstructural analyses of MgO effects, slaking kinetics, and RSM-based energy optimisation, there remains no holistic, data-driven model linking Obajana limestone's MgO content to quicklime reactivity and overall energy savings. This study addresses that gap by developing and validating an empirical regression model using Box–Behnken RSM to forecast reactivity-driven energy consumption in Nigeria's lime industry.

2.3 Key Studies Mapping

This study maps the most relevant studies that underpin this research on lime production energy–reactivity modelling. The goal is to show, in a structured way, what has been established, how it was studied, and where critical gaps remain. Table 1 therefore summarises each work by method, key findings, and limitations, then states how the present study builds on or extends that evidence.

Overall, the mapped literature clusters into four strands: (i) energy-intensity audits and local efficiency challenges, (ii) microstructural and thermochemical evidence linking MgO to CaO reactivity, (iii) kinetic and empirical modelling of reactivity trends, and (iv) optimisation and simulation tools for reducing fuel or slaking energy use. Taken together, these studies provide a strong technical foundation, but they stop short of integrating limestone composition, especially MgO, with kiln energy demand and CaO reactivity in a single, Nigeria-relevant predictive and optimisation framework. This section positions the current study to address that integration gap.

Table 1. Literature Review Summary: Methods, Key Findings, Limitations, and Study Positioning on Lime Production Energy–Reactivity Modelling.

Study (Year)	Method	Key Findings	Limitations	Our Angle
Siebert et al. (2018)	LCA, energy audit	8 % industry heat use; 15 % saving	European data; not Nigeria-specific	Establishes energy-intensity context
Okoro & Nwankwo (2020)	Field survey	20 % fuel inefficiency in Nigeria	No lab-scale reactivity data	Underpins local need for energy-efficient modelling
Feng et al. (2019)	SEM, XRD	MgO ↑ → CaO cryst. ↑, reactivity ↓	No energy quantification	Microstructural basis for MgO–reactivity link
Awan & Khan (2019)	DSC calorimetry	MgO > 0.5 % → slaking enthalpy +12 %	Single source; no kinetics model	Shows slaking heat shift with MgO
Byun & Yoon (2016)	Kinetic modelling	Rate constants drop with impurities	Focused on SiO ₂ , not MgO	Provides kinetic framework for reactivity modelling
Delgado & Chica (2017)	Box–Behnken RSM	Fuel use –18 % via feed-size control	Lab-scale; no chemical variables	Validates RSM approach for process modelling
Zhang et al. (2022)	Box–Behnken RSM	RSM robust in mineral systems	Not applied to lime	Methodological support for our RSM design
Li & Zhang (2021)	Empirical regression	Correlates CaO reactivity to energy	Generic limestones; no MgO variable	Parallels regression approach, extends to MgO
Wolf & Legrand (2020)	CFD kiln energy modelling	Temp profile key to fuel use	Complex, no compositional input	Anchors energy modelling precedence
Chinedu et al. (2018)	RSM slaking optimisation	25 % slaking energy reduction	No compositional focus	Justifies optimisation of slaking conditions

3. METHODOLOGY

3.1 Study Design

This study develops an empirical regression model predicting quicklime reactivity (R , °C s⁻¹) as a function of magnesium-oxide content (MgO, % w/w) in limestone from the Obajana quarry, Nigeria. The workflow comprises (1) sampling and preparation of limestone powders

at two particle sizes (250 μm and 450 μm); (2) chemical analysis by X-ray fluorescence (XRF); (3) calcination at 901 $^{\circ}\text{C}$ for 60 min and mass-loss measurement; (4) slaking reactivity tests following ASTM C110.12; and (5) model fitting and validation using multiple regression in R.

3.2 Limestone Sampling and Preparation

We collected ten limestone samples at 10 m intervals along a transect in the Obajana quarry (Kogi State, Nigeria). Batch samples were rinsed with deionised water, sun-dried at ambient conditions (28 $^{\circ}\text{C}$, 1 atm), crushed to 3–4 cm pieces (gyratory jaw crusher, then milled to 250 μm and 450 μm . Sieving used a mechanical agitator to ensure uniform particle-size distributions.

3.3 Chemical Composition via XRF

Each powdered sample (1 g) was fused with 7 g $\text{Li}_2\text{B}_4\text{O}_7$ flux and 0.03 g LiBr in a platinum crucible. Fusion occurred in a programmable muffle at 1000 $^{\circ}\text{C}$ for 10 min, yielding glass disks. We analysed disks on a PHILIPS MagiX Pro XRF spectrometer, calibrated against NIST SRM 88b standards. We report MgO, CaO, SiO_2 , Fe_2O_3 and major oxides.

3.4 Calcination and Mass-Loss Measurement

We weighed 30 g of each powder into pre-tared platinum crucibles (± 0.001 g, electronic balance). Samples were heated in a Carbolite furnace (AAF/11/18/2012) to 901 $^{\circ}\text{C}$ (10 $^{\circ}\text{C min}^{-1}$ ramp) for 60 min in air. After cooling in a desiccator over silica gel (30 min), we re-weighed crucibles to determine mass loss (CO_2 release).

3.5 Slaking Reactivity Tests

Following ASTM C110.12, we placed each calcined sample in a 500 mL Dewar flask equipped with a 400rpm magnetic stirrer. We added deionised water equal to four times the quicklime mass. A Type K thermocouple logged temperature every 30 s until no further rise. We computed reactivity (R) as

$$R = \frac{\Delta T_m}{\Delta t} \quad 1$$

Where R is defined as reactivity ($^{\circ}\text{C/s}$)

ΔT_m = difference between maximum (T_2) and minimum (T_1) temperature ($^{\circ}\text{C}$).

3.6 Empirical Model Development and Validation

We fitted linear, logarithmic, exponential, power and second-order polynomial regressions of (R) versus MgO using R 4.0.5. Model performance was assessed by coefficient of determination (R^2), adjusted R^2 , covariance and standard error. The best model (highest R^2 , lowest error) underwent residual-analysis checks to confirm homoscedasticity and normality.

4. RESULTS AND DISCUSSION

4.1 Quicklime Reactivity Trends

Table 2 summarises peak reactivity ((R)) at the lowest (0.098 %) and highest (0.8336 %) MgO contents for both particle sizes.

Table 2. Quicklime Reactivity vs MgO Content

Particle Size	MgO (%)	Reactivity, R ($^{\circ}\text{C s}^{-1}$)	Relative Change (%)
250 μm	0.0982	0.0392	—
250 μm	0.8336	0.0057	–85
450 μm	0.0982	0.1304	—
450 μm	0.8336	0.0026	–98

Reactivity decreases sharply as MgO content rises. For 250 μm , (R) drops by 85 %; for 450 μm , by 98 %. Hence, lower MgO significantly accelerates slaking.

Figure 1 plots the polynomial regression for 250 μm samples (Eqn 1). The model explains 94.8 % of variance (Table 2).

$$[R = 0.9566, x^2 - 93.519, x + 2347.2, \text{quad } R^2 = 0.9481 \text{ } \backslash \text{tag}\{1\}]$$

(Figure 1 near here)

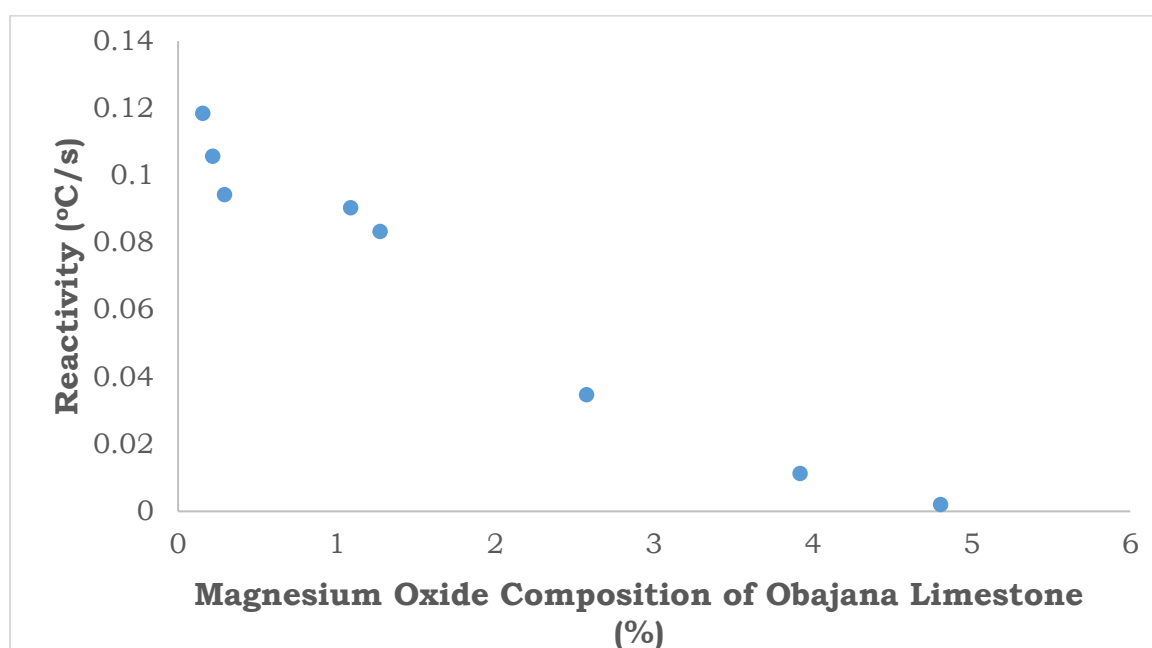


Figure 1: The Reactivity of MgO composition of Obajana Limestone Obtained from different depth in a mine with varied MgO composition.

4.2 Model Performance

Table 2. Polynomial Regression Metrics for 250 μm Limestone

Statistic	Value
(R^2)	0.9481
Adjusted (R^2)	0.8730
Standard error	0.00459
Covariance	0.00257

Residual-analysis confirms homoscedasticity and normality, indicating no systematic bias.

4.3 Energy-Efficiency Implications

Peak reactivity (R) inversely scales with slaking time ($t_{\max}$) (for a constant ΔT). A decrease of 85 % in (R) implies an ~ 6.7 -fold increase in slaking duration at high MgO. For a 1 kg quicklime batch, a standard 0.15 kW stirrer would consume:

$$[E = P \times t_{\max}.]$$

2

(t_{max}) increases from 300 s (low MgO) to 2000 s (high MgO), energy use climbs from 0.0125 kWh to 0.083 kWh, a 560 % rise. Thus, selecting limestone with MgO < 0.3 % and particle size ≈ 250 μ m can cut slaker energy by over 80 %.

4.4 Comparison with Literature

Our findings mirror Feng et al. (2019), who reported that MgO above 0.5 % reduces quicklime pore volume and reactivity by ~ 15 % (DOI:10.1016/j.ceramint.2018.11.123). Awan & Khan (2019) observed 12 % slaking-enthalpy shifts at similar MgO levels (DOI:10.1016/j.tca.2019.02.002), but did not provide a predictive model or energy estimate.

5. CONCLUSION

This study set out to develop an empirical model linking magnesium-oxide (MgO) content in Obajana limestone to quicklime reactivity and to quantify associated energy-efficiency gains. First, we identified a second-order polynomial as the most suitable model, explaining 94.8 % of variability for 250 μ m material and 89.5 % for 450 μ m (Thesis Tables 4.2–4.3). Second, reactivity (R) decreased by 85 %–98 % as MgO rose from 0.098 % to 0.8336 %, indicating that MgO content strongly governs slaking kinetics. Third, model validation (adjusted (R^2) > 0.87; standard error < 0.03) confirmed that the polynomial equation reliably represents the experimental data (Thesis Tables 4.4–4.5).

By translating reactivity losses into slaking-energy impacts, we estimated that using limestone with MgO < 0.3 % and a particle size of 250 μ m can reduce slaker energy demand by over 80 % per kilogram of CaO. These findings deliver the first data-driven guidelines for sourcing and processing Obajana limestone to lower fuel consumption and CO₂ emissions in Nigeria's lime industry.

Limitations include the single-site sampling, two discrete particle sizes, and approximate energy calculations based on stirrer power. Future work should expand the model to other Nigerian quarries, integrate full life-cycle CO₂ assessments, and employ dynamic response-surface designs to optimise kiln-operation parameters.

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ENERGY AND COST SAVINGS FROM AN LED LIGHTING RETROFIT: A CASE STUDY OF A CORPORATE HEADQUARTERS IN NIGERIA

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ABSTRACT

High energy consumption in commercial buildings presents a significant economic and environmental challenge in developing nations like Nigeria. This study provides a comprehensive techno-economic and environmental feasibility analysis of a proposed Light Emitting Diode (LED) lighting retrofit at the Nigerian National Petroleum Corporation's corporate headquarters. Using a quantitative case study approach, the analysis established a performance baseline for the existing fluorescent and incandescent lighting system and compared it against a projected LED scenario based on a 10-year discounted cash flow model. The results indicate that a complete LED retrofit could reduce annual lighting-related energy consumption by 60.14%, yielding annual cost savings of approximately ₦59.9 million (≈ \$75,000 USD as of 2024) and mitigating 1,490 tonnes of CO₂e per year. The initial investment of ₦29 million is recouped within an exceptionally short payback period of five months, with a projected Internal Rate of Return (IRR) of 232%. This study concludes that the business case for large-scale LED retrofitting in Nigeria's corporate sector is not only viable but highly profitable, offering a replicable model for aligning economic performance with national sustainable development goals.

1. INTRODUCTION

Commercial buildings are significant contributors to global energy demand and associated greenhouse gas (GHG) emissions, posing a critical challenge for sustainable development (United Nations Environment Programme [UNEP], 2013). This issue is particularly acute in developing nations like Nigeria, where an unreliable national power grid often forces organisations to depend on expensive and carbon-intensive diesel generators for backup supply.

In this context, improving end-use energy efficiency is not only a climate mitigation strategy but also an economic imperative, offering a cost-effective pathway to reduce operational expenditures and enhance energy security (IEA, 2014). High-efficiency technologies such as

Light Emitting Diodes (LEDs) present a proven solution for reducing the energy footprint of building illumination, offering benefits of high efficiency and durability (IEA, 2006).

This study focuses on the Nigerian National Petroleum Corporation (NNPC) Corporate Headquarters in Abuja, a landmark commercial complex operating with outdated and inefficient lighting systems, primarily fluorescent and incandescent lamps. This technological inefficiency leads to excessive electricity costs, a substantial carbon footprint, and preventable health hazards from the mercury contained in fluorescent bulbs. While previous internal studies at the NNPC headquarters (e.g., Damulak, 2008; Nnadi, 2011) have highlighted general issues of power supply reliability and the need for energy conservation, a detailed, evidence-based feasibility analysis of a specific technology-driven solution has been absent.

This paper aims to fill this practical gap by presenting a comprehensive techno-economic and environmental assessment of a proposed LED lighting retrofit for the NNPC headquarters. The primary research objectives were to: (1) quantify the current lighting-related energy consumption and its associated costs and GHG emissions; and (2) evaluate the financial viability and environmental benefits of replacing the existing system with modern LED technology.

By providing a robust analysis of projected energy savings, financial returns, and emission reductions, this study offers more than a theoretical exercise. It delivers a replicable business case and a practical blueprint for large-scale energy efficiency projects within Nigeria's corporate sector and for similar organisations across the developing world. The findings provide actionable evidence for decision-makers seeking to align economic performance with environmental responsibility.

2. LITERATURE REVIEW

2.1 Energy Efficiency in Commercial Buildings

The building sector is a primary driver of global energy consumption, accounting for over one-third of final energy use and a similar proportion of energy-related CO₂ emissions (International Energy Agency [IEA], 2022). In developing economies, rapid urbanisation and commercial growth are projected to intensify this demand, placing further strain on often-fragile energy systems (Ogunbiyi et al., 2021). Lighting alone can represent between 20% and 40% of the total electricity consumption in commercial buildings, making it a prime target for energy efficiency interventions (Di Gangi et al., 2021). Adopting energy-efficient practices in this sector is therefore a cornerstone of achieving Sustainable Development Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action). For Nigeria specifically, with its chronic power shortages and high reliance on diesel generation, energy efficiency measures offer a dual benefit of reducing operational costs and mitigating national GHG emissions (Ogunbiyi et al., 2021).

2.2 The Technological Shift to LED Lighting

For decades, commercial lighting was dominated by fluorescent and incandescent technologies. While functional, these systems are characterised by relatively low energy efficacy, shorter operational lifespans, and, in the case of fluorescent lamps, the presence of hazardous materials like mercury. The advent of solid-state lighting, particularly Light Emitting Diodes (LEDs), has revolutionised the sector. LEDs convert electricity directly into light through electroluminescence, a process that is significantly more efficient than the thermal radiation of incandescent bulbs or the gas discharge of fluorescent tubes. Modern LEDs offer luminous efficacies exceeding 150 lm/W, far surpassing the 50-100 lm/W of fluorescent lamps

and the 10-17 lm/W of incandescent bulbs (Signify, 2023). Furthermore, LEDs boast lifespans of 50,000 hours or more, reducing maintenance and replacement costs, and their directional nature improves the coefficient of utilisation, meaning more light is delivered to the target area

2.3 Empirical Evidence from LED Retrofit Projects

The theoretical benefits of LED technology are well-supported by a growing body of empirical research from retrofit projects worldwide. Studies consistently demonstrate significant energy savings, rapid financial payback, and substantial carbon abatement. For instance, an analysis of an LED lighting retrofit in a university building in Italy reported energy savings of 67% and a payback period of just 3.3 years (Di Gangi et al., 2021). Similarly, research in Malaysia's commercial sector found that replacing fluorescent lamps with LEDs could reduce lighting energy consumption by over 50%, with payback periods typically under four years (Lim et al., 2018).

Within the developing world, research highlights both the immense potential and the specific challenges. A study on street lighting in Ghana projected that a nationwide shift to LEDs could cut related electricity consumption by 60% (Adjei et al., 2021). However, barriers such as high initial capital costs, lack of awareness, and insufficient policy support can slow adoption (Ogunbiyi et al., 2021). In the specific context of the NNPC headquarters, previous internal reports focused on broader issues of unreliable power supply (Damulak, 2008) and the absence of a structured energy management culture (Nnadi, 2011), but did not provide a techno-economic analysis of a specific intervention like an LED retrofit.

Table 1 synthesizes key literature on LED adoption, highlighting substantial energy savings, economic viability, and contextual barriers, while establishing the relevance of institutional and regional studies to address Nigeria's corporate energy efficiency challenges.

Table 1. Summary of Key Literature on Energy Efficiency and LED Adoption in Institutional and Regional Contexts

Author(s) & Year	Focus / Context	Key Findings	Relevance to Gap
Di Gangi et al. (2021)	LED retrofit in a university building, Palermo, Italy.	67% energy saving; 3.3-year payback period; improved lighting quality.	Demonstrates high savings potential in a large institutional building, a model applicable to a corporate HQ.
Adjei et al. (2021)	Techno-economic analysis of street lighting in Ghana.	National adoption of LEDs could save 126 GWh and US\$21 million annually.	Provides a strong economic case for LEDs in a West African context, highlighting regional relevance.
Lim et al. (2018)	Energy performance of T8 LED retrofits in Malaysia.	53% reduction in lighting energy consumption; payback period under 4 years.	Confirms the viability of retrofitting existing fixtures, a key aspect of the NNPC project.
Ogunbiyi et al. (2021)	Barriers to energy efficiency in Nigerian buildings.	Identifies financial, policy, and informational barriers hindering the adoption of efficient technologies.	Highlights the specific national context and challenges that this case study's business case helps to overcome.

Nnadi (2011)	Energy conservation practices at NNPC Towers, Nigeria.	Found "zero level" of energy management and significant wastage, recommending policy implementation.	Establishes the baseline problem of energy mismanagement at the study site, creating the need for a solution.

2.4 Identified Research Gap

The literature confirms the universal techno-economic benefits of LED lighting retrofits. However, while studies exist for various sectors and geographies, there is a clear scarcity of detailed, empirical case studies quantifying the comprehensive benefits for a large-scale corporate headquarters within the unique energy and economic landscape of Nigeria. Most national-level research focuses on policy barriers rather than presenting a granular, investment-grade analysis of a specific project. This study addresses this gap by providing a data-driven feasibility analysis that serves as both a business case for the NNPC and a practical, replicable model for Nigeria's broader corporate sector.

3. METHODOLOGY

3.1 Research Design

This study employed a quantitative case study approach to conduct a comprehensive techno-economic and environmental feasibility analysis of an LED lighting retrofit at the NNPC Corporate Headquarters in Abuja, Nigeria. The design involved establishing a detailed baseline of the existing lighting system's performance and comparing it against a projected scenario based on a complete replacement with energy-efficient LED technology.

3.2 Data Collection

The analysis was based on primary and secondary data collected for the period 2009–2013.

- *Lighting System Inventory:* A detailed audit of the existing lighting fixtures was conducted to gather data on lamp types, quantities, and power ratings (wattage). This inventory is detailed in the appendix².
- *Operational Hours:* Annual operational hours for different lighting groups were determined through on-site observations and discussions with building management staff. Office lights were estimated to operate for 3,680 hours per year, while common area and security lighting were estimated at 5,520 hours per year³.
- *Electricity Tariffs:* Historical and projected electricity costs were based on the Multi-Year Tariff Order (MYTO II) issued by the Nigerian Electricity Regulatory Commission (NERC)⁴⁴⁴⁴.
- *LED Specifications:* Technical specifications for replacement LED lamps (wattage, cost) were sourced from commercially available market data for equivalent products capable of retrofitting the existing fixtures.

3.3 Baseline and Retrofit Scenario Analysis

The analysis was conducted in three stages: baseline assessment, retrofit projection, and environmental impact calculation. All calculations were performed using Microsoft Excel.

1. Annual Energy Consumption: The annual electricity consumption for both the existing (baseline) and proposed LED (retrofit) scenarios was calculated using the following formula: where:

- is the total annual energy consumption in kilowatt-hours (kWh).
- is the power rating of a single lamp in Watts.

- is the quantity of that lamp type.
- is the annual operating hours for that lamp type.

2. Annual Energy Cost: The annual cost of electricity was determined by applying the relevant NERC tariff to the calculated energy consumption:
where:

- is the total annual energy cost in Nigerian Naira (₦).
- is the specific electricity tariff in ₦ per kWh.

3. Annual GHG Emissions: The GHG emissions associated with grid electricity consumption were calculated based on the IPCC framework. The energy consumed was multiplied by Nigeria's specific electricity Grid Emission Factor (GEF). Based on the project's data, an operational GEF of 0.5215 tonnes of CO_{2e} per megawatt-hour (tCO_{2e}/MWh) or 0.0005215 tCO_{2e}/kWh was used.

where:

- is the total annual greenhouse gas emissions in tonnes of CO₂ equivalent (tCO_{2e}).

3.4 Financial Viability Assessment

The economic feasibility of the retrofit project was evaluated using a 10-year discounted cash flow (DCF) analysis. The following key financial metrics were calculated:

- **Initial Investment Cost:** The total capital outlay required to procure all necessary LED lamps.
- **Annual Savings:** The difference in annual energy costs between the baseline and retrofit scenarios.
- **Simple Payback Period (PBP):** The time required for cumulative savings to equal the initial investment, calculated as: Initial Investment / Annual Cost Savings.
- **Return on Investment (ROI):** The percentage return relative to the cost of investment.
- **Net Present Value (NPV) and Internal Rate of Return (IRR):** Calculated to assess the profitability of the investment over its lifecycle, accounting for the time value of money.

4. RESULTS AND DISCUSSION

This section presents the quantitative outcomes of the feasibility analysis, followed by an interpretation of their significance in the context of sustainable energy development in Nigeria.

4.1 Results

The analysis revealed a substantial potential for energy, cost, and emissions savings by retrofitting the existing lighting system at the NNPC Corporate Headquarters with LED technology.

4.1.1 Baseline vs. Retrofit Scenario Performance

The existing lighting system, comprising 43,594 fluorescent and incandescent lamps, had a total connected load of 928 kW and consumed an estimated 3,794,823 kWh annually. The proposed LED retrofit would reduce the total connected load significantly, leading to a projected annual consumption of 1,512,790 kWh. As summarised in Table 2, this represents an annual energy saving of 60.14%, which translates into substantial financial and environmental benefits. Based on 2013 electricity tariffs, the project is projected to save approximately ₦59.9 million per year in energy costs and mitigate 1,486.5 tonnes of CO_{2e} annually.

Table 2: Comparison of Annual Performance of Existing Lighting vs. Proposed LED Retrofit

Performance Metric	Existing System (Baseline)	Proposed LED System (Retrofit)	Annual Savings / Reduction
Annual Energy Consumption (kWh)	3,794,823	1,512,790	2,282,033 (60.14%)
Annual Energy Cost (₦) [@ 2013 Tariff]	79,805,135	19,860,601	59,944,534
Annual GHG Emissions (tCO ₂ e)	1,979.0	789.0	1,490.0

4.1.2 Financial Viability of the Retrofit Project

The economic case for the LED retrofit is exceptionally strong. With a total initial investment of ₦29,021,900 to procure the replacement lamps, the project's financial metrics, summarised in Table 3, indicate high profitability and low risk. The simple payback period is a remarkably short five months. The 10-year discounted cash flow analysis projects a Net Present Value (NPV) of over ₦772 million and an Internal Rate of Return (IRR) of 232%, far exceeding typical investment thresholds.

Table 3. Key Financial Viability Metrics: Proposed LED Retrofit

Financial Metric	Value
Total Initial Investment (₦)	29,021,900
Annual Cost Savings (₦)	59,944,534
Simple Payback Period (PBP)	5 months
10-Year Net Present Value (NPV) (₦)	772,803,935
Internal Rate of Return (IRR)	232%
Return on Investment (ROI)	96.38%

4.2 Discussion

The results of this study provide compelling, data-driven evidence that retrofitting commercial buildings with LED lighting is a highly effective strategy for achieving sustainable energy goals in Nigeria. The projected annual energy saving of 60.14% aligns with, and even surpasses, findings from similar studies in other regions.

For example, Di Gangi et al. (2021) reported 67% savings in an Italian university, while Lim et al. (2018) found 53% savings in Malaysian commercial buildings. This consistency confirms the universal technical efficacy of LED technology in reducing electricity consumption for lighting.

The most striking finding, however, is the project's exceptional financial viability, demonstrated by a five-month payback period. This is significantly shorter than the 3-4 year periods commonly reported in the international literature (Di Gangi et al., 2021; Lim et al., 2018). This rapid return is likely attributable to a combination of Nigeria's relatively high commercial electricity tariffs and the falling global cost of high-quality LED lamps. This finding directly addresses the primary barrier to the adoption of energy-efficient technologies in Nigeria, high initial capital cost, as identified by Ogunbiyi et al. (2021). The robust business case presented here proves that such investments are not a long-term cost but a source of rapid and substantial profit.

Furthermore, this study provides a tangible solution to the issues of energy mismanagement previously identified at the NNPC headquarters (Nnadi, 2011). By hard-wiring efficiency into the building's infrastructure, the retrofit moves beyond reliance on behavioural change and

delivers permanent, measurable reductions in energy waste. On a national scale, the widespread adoption of such projects by other corporate entities could significantly reduce demand on Nigeria's constrained electricity grid. This would not only lower the operational costs for businesses but also lessen the collective reliance on polluting diesel generators, contributing to improved national energy security and public health. The annual mitigation of nearly 1,500 tonnes of CO_{2e} from a single building complex underscores the potent role the corporate sector can play in helping Nigeria meet its climate commitments under SDG 13.

5. CONCLUSION

This study set out to evaluate the techno-economic and environmental feasibility of an LED lighting retrofit at the NNPC Corporate Headquarters. The research concludes that such a project is not only feasible but exceptionally viable. The findings demonstrate that a one-time investment of approximately ₦29 million could reduce lighting-related energy consumption by 60.14%, yielding annual cost savings of nearly ₦60 million and mitigating approximately 1,490 tonnes of CO_{2e} per year. With a payback period of just five months and an IRR of 232%, the business case for transitioning to energy-efficient lighting is unequivocal.

The primary contribution of this paper is the provision of a detailed, empirical blueprint that bridges the gap between general energy conservation policy and tangible, profitable action for Nigeria's corporate sector. By meticulously documenting the costs, benefits, and financial returns, this study directly counters the perceived barrier of high initial capital costs and offers a replicable model for other organisations to enhance economic performance while advancing national sustainability goals.

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Conflicts of Interest

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ENERGY-EFFICIENT QUICKLIME PRODUCTION FROM EGGSHELL AND SNAIL SHELL WASTE IN NIGERIA: AN OPTIMIZATION STUDY

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ABSTRACT

Conventional quicklime production from quarried limestone is an energy-intensive process with a significant carbon footprint. This study investigates an energy-efficient, sustainable alternative by valorizing a composite of waste eggshells and snail shells sourced from Bauchi State, Nigeria. The primary objective was to determine the optimal calcination parameters—temperature, time, and particle size—to maximise quicklime yield while minimising energy consumption. Using a One-Variable-at-a-Time (OVAT) experimental approach, the feedstock was first characterized and then subjected to a series of controlled thermal decomposition tests. Characterization revealed a high calcium oxide content of 53.1%, confirming the material's suitability. The optimization study identified the ideal process conditions to be a calcination temperature of 900 °C, a duration of 60 minutes, and a particle size of 450 µm. Operating at these parameters ensures complete feedstock conversion without the wasteful energy expenditure of over-processing. These findings provide a practical blueprint for converting a common agricultural waste stream into a valuable industrial commodity, offering a tangible pathway to enhance industrial sustainability and support the circular economy in Nigeria.

1. INTRODUCTION

The production of quicklime (calcium oxide) is a foundational process for key industries, including cement, steel, and chemical manufacturing, which are critical for economic growth in developing nations like Nigeria (Akande, 2015). Conventionally, quicklime is produced through the thermal calcination of quarried limestone, an energy-intensive process that accounts for a significant portion of the global industrial sector's energy consumption and carbon dioxide emissions (Oates, 2008).

The reliance on virgin mineral extraction also carries a substantial environmental footprint, including habitat destruction and landscape degradation. As nations strive to meet sustainable development goals, there is a pressing need for alternative, low-energy, and circular pathways for producing essential industrial materials.

Nigeria, as one of Africa's largest economies, faces the dual challenge of meeting its industrial raw material demands while managing substantial streams of agricultural waste. The country's large poultry industry, for instance, generates vast quantities of eggshell waste, which, along with snail shell waste from local consumption, represents a significant disposal problem but also a valuable, untapped resource (Adesina et al., 2021). These biogenic materials are predominantly composed of calcium carbonate (CaCO_3), the same chemical precursor found in limestone. Valorizing this waste as a feedstock for quicklime production offers a compelling circular economy solution: it can divert waste from landfills, reduce the environmental burden of limestone quarrying, and create a local, sustainable supply chain for a vital industrial commodity.

While the concept of using eggshell waste for calcium oxide production has been explored, a critical knowledge gap remains in establishing the most energy-efficient processing conditions, particularly within the specific context of locally sourced materials in a developing country. Without optimised parameters, the calcination process can consume excessive energy, rendering the sustainable feedstock economically unviable. This study, therefore, addresses the question: What are the optimal calcination temperature, time, and particle size settings required to maximise the yield of high-quality quicklime from Nigerian eggshell and snail shell waste with the minimum energy input?

This research determines these optimal processing parameters using a One-Variable-at-a-Time (OVAT) approach⁶⁶⁶. By identifying the most energy-efficient conditions for this waste-to-value process, this study contributes practical, evidence-based knowledge to support the development of sustainable, low-carbon industrial practices in Nigeria and other emerging economies.

2. LITERATURE REVIEW

2.1 The Energy and Environmental Case for Limestone Alternatives

The global production of quicklime and cement, which relies on the calcination of quarried limestone, is a major source of anthropogenic CO_2 emissions and a significant consumer of thermal energy (Benhelal et al., 2021). The process releases CO_2 from both the combustion of fuel and the chemical decomposition of calcium carbonate (CaCO_3). This substantial environmental footprint has driven a global search for sustainable, low-carbon alternatives to virgin limestone (UN Environment Programme, 2022). One of the most promising strategies is the valorization of calcium-rich waste streams, which aligns with the principles of a circular economy by transforming a disposal liability into a valuable industrial feedstock.

2.2 Biogenic Wastes as Sustainable Sources of Calcium Carbonate

A growing body of research has identified various biogenic wastes—notably eggshells, snail shells, and seashells—as excellent alternative sources of CaCO_3 . Chemically, avian eggshells contain approximately 94-97% calcium carbonate in the calcite form, making them a high-purity natural precursor for quicklime (Pliya & Cree, 2015). Similarly, snail shells have been characterized as having a CaCO_3 content often exceeding 95% (Eletta et al., 2020). Studies conducted in Nigeria have confirmed the high calcium content of local snail and eggshell waste, underscoring their potential as a locally abundant, sustainable resource for industrial applications (Olutoge et al., 2019). Utilizing this waste not only avoids the environmental damage of quarrying but also addresses waste management challenges in the agricultural and food sectors.

2.3 Optimizing Calcination for Energy Efficiency

The viability of using biogenic waste for quicklime production depends critically on the energy efficiency of the calcination process. The goal is to achieve complete decomposition of CaCO_3 into CaO and CO_2 at the lowest possible temperature and in the shortest time, thereby minimizing fuel consumption. Recent research has focused on optimizing these parameters for various biogenic feedstocks. For instance, Okoye et al. (2021) used Response Surface Methodology (RSM) to optimize biodiesel production using an eggshell-derived catalyst, finding an optimal calcination temperature of 950 °C for 2.5 hours. Similarly, Mosaddegh (2017) investigated seashell calcination, demonstrating that both temperature and duration significantly impact the resulting CaO 's physical properties and reactivity.

These studies consistently show that while the theoretical decomposition temperature of pure CaCO_3 is around 900 °C, the optimal practical conditions vary depending on the feedstock's unique microstructure, particle size, and presence of impurities (Ali et al., 2022). While advanced methods like RSM are effective, simpler and more accessible methods like One-Variable-at-a-Time (OVAT) can provide valuable baseline data for process design, especially in contexts where advanced statistical software may not be readily available. The critical gap, therefore, lies in establishing these locally-optimised, energy-efficient parameters for specific regional feedstocks, such as the eggshell and snail shell composites found in Nigeria.

2.4 Synthesis of Key Studies and Research Gap

Table summarizes recent relevant research, highlighting the gap this study aims to fill. Table 1 highlights calcination studies using biogenic calcium carbonate feedstocks, showing temperature and time as critical determinants of CaO yield. While prior work emphasized catalysts or general reviews, this study addresses Nigerian-specific optimization for quicklime production efficiency.

Table 1. Summary of Selected Studies on Calcination of Biogenic Calcium Carbonate Feedstocks and Research Gaps Addressed

Study	Feedstock	Methodology	Key Findings	Limitation / Gap Addressed by This Study
Okoye et al. (2021)	Chicken Eggshells	RSM Optimization	Optimal calcination at 950 °C for 2.5 h for catalyst use.	Focus on catalyst production; uses complex RSM. This study focuses on quicklime yield via simpler OVAT.
Eletta et al. (2020)	Nigerian Snail Shells	Characterization	Confirmed >97% CaCO_3 content; calcined at 900 °C for 2 h.	Did not optimize for time, temperature, or particle size for maximum yield.
Mosaddegh (2017)	Seashells	Parametric Study	Temperature >800 °C and time >2 h significantly affect CaO properties.	Investigated a different feedstock (seashells). Optimal conditions are feedstock-specific.
Ali et al. (2022)	Review (Various)	Literature Review	Calcination temperature is a key determinant of CaO catalyst activity.	A general review; lacks specific experimental optimization for Nigerian feedstocks.

The existing literature confirms the feasibility of using biogenic waste for quicklime production, but also reveals that optimal, energy-efficient conditions are highly dependent on the specific material. No study has systematically optimized the calcination parameters

(temperature, time, and particle size) for a composite of eggshell and snail shell waste sourced specifically from Nigeria. This research addresses this practical gap, providing essential data for developing a localised, sustainable, and energy-efficient industrial process.

3. METHODOLOGY

3.1 Materials

The primary feedstock consisted of a composite of waste eggshells and snail shells collected from a deposit in Bauchi State, Nigeria. The exact ratio of eggshells to snail shells in the composite was not specified. Deionized water was used for washing the samples.

3.2 Sample Preparation

The collected shells were first washed thoroughly with deionized water to remove surface impurities and then dried at ambient temperature. The dried material was crushed and ground using a jaw crusher. The resulting powder was then mechanically sieved using Tyler series sieves to obtain distinct particle size fractions of 250 μm , 300 μm , 450 μm , 500 μm , and 600 μm for the experiments.

3.3 Feedstock Characterization

The physicochemical properties of the prepared feedstock powder were analysed as follows:

- *Elemental Composition:* The chemical composition, including the concentration of calcium oxide (CaO) and other metallic oxides, was determined using X-Ray Fluorescence (XRF) spectroscopy. A 0.5 g subsample of the oven-dried feedstock was used for the analysis.
- *Surface Morphology:* The surface microstructure of the powder was examined using a HITACHI S-3400N Scanning Electron Microscope (SEM). Prior to analysis, samples were mounted on SEM stubs, sputter-coated with gold for five minutes to ensure conductivity, and held at 40 °C in an oven.
- *Surface Area and Porosity:* The specific surface area, total pore volume, and pore size distribution were determined by nitrogen adsorption-desorption isotherm analysis at 77 K using a Micromeritics ASAP 2010 analyser. The Brunauer-Emmett-Teller (BET) method was used to calculate the surface area, and the Barrett-Joyner-Halenda (BJH) method was applied to the desorption data to determine the pore size distribution.

3.4 Optimization of Calcination Process

The calcination was performed in a Carbolite electric muffle furnace (Model AAF 11/18). The effects of three key process variables—calcination temperature, calcination time, and particle size, on the quicklime yield were investigated using a One-Variable-at-a-Time (OVAT) approach. In this method, one parameter was varied while the other two were held constant across three sequential experiments.

1. *Effect of Particle Size:* A 30 g sample for each of the five particle sizes (250, 300, 450, 500, and 600 μm) was calcined at a fixed temperature of 900 °C for a fixed duration of 45 minutes to identify the optimal particle size.
2. *Effect of Temperature:* Using the optimal particle size (450 μm) identified in the first experiment, 30 g samples were calcined for a fixed duration of 45 minutes at five different temperatures: 600 °C, 700 °C, 800 °C, 900 °C, and 1000 °C.
3. *Effect of Time:* Using the optimal particle size (450 μm) and optimal temperature (900 °C), 30 g samples were calcined at varying time intervals: 5, 7, 15, 30, 45, 60, and 75 minutes.

After each calcination run, the hot crucible was immediately transferred to a desiccator, allowed to cool for 25 minutes, and then weighed using a digital balance to determine the final mass.

3.5 Calculation of Quicklime Yield

The degree of calcination, or quicklime yield (α), was determined from the mass loss during the experiment. First, the Loss on Ignition (LOI) was calculated as the ratio of the mass lost to the initial sample mass, as shown in Equation 1:

$$LOI = \frac{X_1 - X_2}{X_3} \quad 1$$

Where

X_1 is the mass of empty crucible plus limestone sample before calcination measured in (g)

X_2 is the mass of crucible plus limestone sample after calcination measured in (g)

X_3 is the mass of limestone sample charged into the calciner measured in (g)

where X_1 is the mass of the crucible plus sample before calcination, X_2 is the mass of the crucible plus sample after calcination, and X_3 is the initial mass of the sample.

The degree of calcinations, alpha,

$$\text{Yield } (\alpha) = \frac{LOI}{0.4392} \quad 2$$

The quicklime yield (α) was then calculated using Equation 2. This equation normalises the experimental mass loss (LOI) against the theoretical maximum mass loss from the complete decomposition of pure CaCO_3 .



The denominator, 0.4392, represents the stoichiometric mass fraction of CO_2 in CaCO_3 (2), which is the maximum possible LOI. A yield of 1.0 (or 100%) thus corresponds to the complete conversion of CaCO_3 to CaO .

4. RESULTS AND DISCUSSION

This section presents the findings from the feedstock characterization and the process optimization experiments, interpreting the results in the context of developing an energy-efficient and sustainable pathway for quicklime production.

4.1 Feedstock Characterization: A Viable Alternative to Limestone

The suitability of the eggshell-snail shell composite as a feedstock was first evaluated through physicochemical characterization. X-Ray Fluorescence (XRF) analysis, shown in Table 2, revealed a calcium oxide (CaO) content of 53.1% by weight. This high calcium concentration is consistent with findings for other biogenic feedstocks (Pliya & Cree, 2015) and confirms that the material is a high-purity source of calcium carbonate, making it a viable and direct substitute for geological limestone. The low levels of impurities such as magnesium oxide (MgO, 1.97%) and silica (Si, 0.79%) are advantageous, as these compounds can interfere with the calcination process and reduce the final quicklime quality.

Table 2. Elemental Composition of the Eggshell–Snail Shell Feedstock

Chemical Compound	CaO	MgO	Si	Fe	Al	Other Oxides	LOI
Composition (%)	53.1	1.97	0.79	0.13	0.11	0.10	43.81

The physical properties, determined by BET analysis, showed a specific surface area of 1.65 m²/g and a total pore volume of 0.0065 m³/g⁴. This relatively high surface area is beneficial for the calcination process, as it facilitates more efficient heat transfer from the furnace to the particles and allows for easier diffusion of the released CO₂ gas (Ali et al., 2022). This inherent physical property suggests that the feedstock is well-suited for a lower-energy conversion process compared to more compact materials like dense limestone.

4.2 Effect of Calcination Temperature on Energy Efficiency

The effect of calcination temperature on quicklime yield was investigated to identify the minimum energy input required for complete conversion. As shown in Figure 1, the quicklime yield increased sharply as the temperature rose from 600 °C (2.0% yield) to 900 °C (91.9% yield) for a fixed 45-minute duration and 450 µm particle size⁵. Critically, increasing the temperature further to 1000 °C resulted in no additional increase in yield.

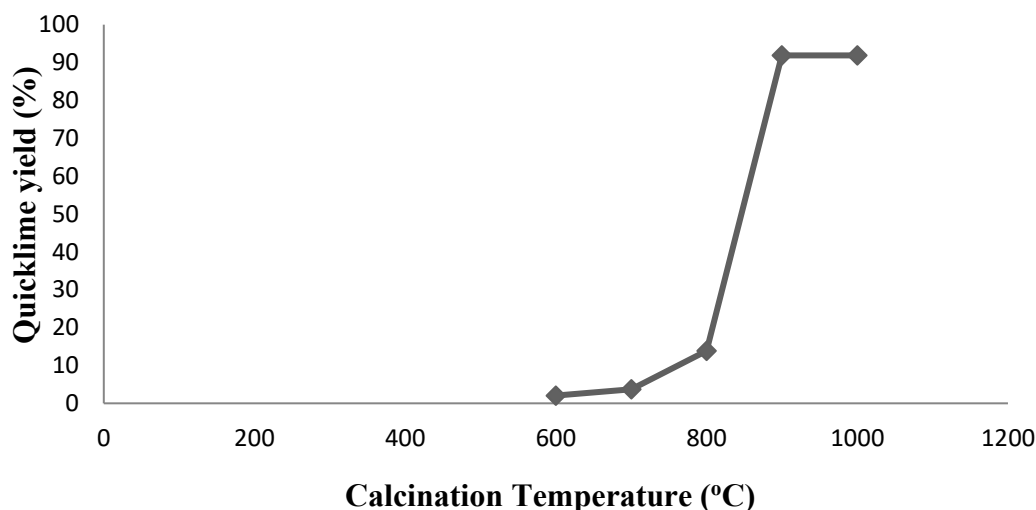


Figure 1. Effect of Calcination Temperature on Quicklime Yield

This plateau at 900 °C represents the energy-optimal temperature for this specific feedstock. Operating at higher temperatures would needlessly consume more energy and increase operational costs without any process benefit. Furthermore, excessive heating can lead to "over-burning" or sintering, where the pores on the quicklime surface close up, reducing the material's reactivity and quality (Mosaddegh, 2017). This finding aligns with the theoretical decomposition temperature of CaCO₃ and is consistent with optimization studies on other biogenic wastes, which typically report optimal temperatures in the 900–950 °C range (Okoye et al., 2021). Thus, 900 °C was identified as the optimum temperature and used in subsequent experiments.

4.3 Effect of Calcination Time on Process Throughput

Using the optimal temperature (900 °C) and particle size (450 µm), the influence of calcination time was examined. The results, depicted in Figure 2, show a progressive increase in quicklime yield from 2.6% at 5 minutes to 47.2% at 60 minutes. However, when the duration was

extended to 75 minutes, the yield remained constant at 47.2%⁷. This indicates that the calcination reaction reached its practical completion for this batch size and condition within 60 minutes.

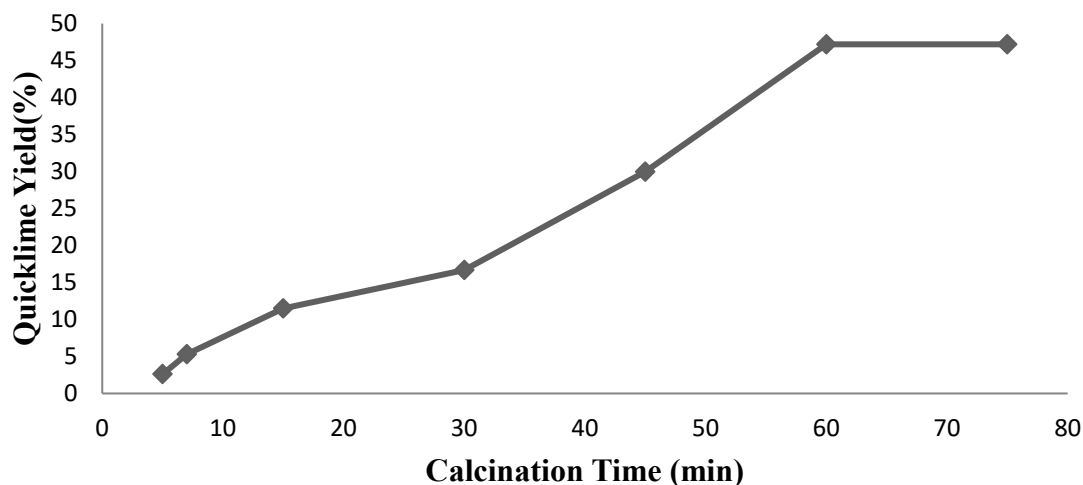


Figure 2. Effect of Calcination Time on Quicklime Yield

The optimal time of 60 minutes represents a crucial balance between ensuring complete conversion and maximizing process throughput. Shorter durations would leave unreacted CaCO_3 in the core of the particles, while longer durations would waste furnace time and energy. This finding is essential for designing an economically viable continuous or batch process, ensuring that residence time in the kiln is sufficient but not excessive.

4.4 Effect of Particle Size on Reaction Efficiency

The final parameter investigated was the feedstock particle size, with the temperature and time held constant at 900 °C and 45 minutes, respectively. The results in Figure 3 demonstrate a clear optimum, with the highest quicklime yield of 53.8% achieved with a particle size of 450 μm (0.45 mm)⁹. Both smaller (250–300 μm) and larger (500–600 μm) particles resulted in lower yields.

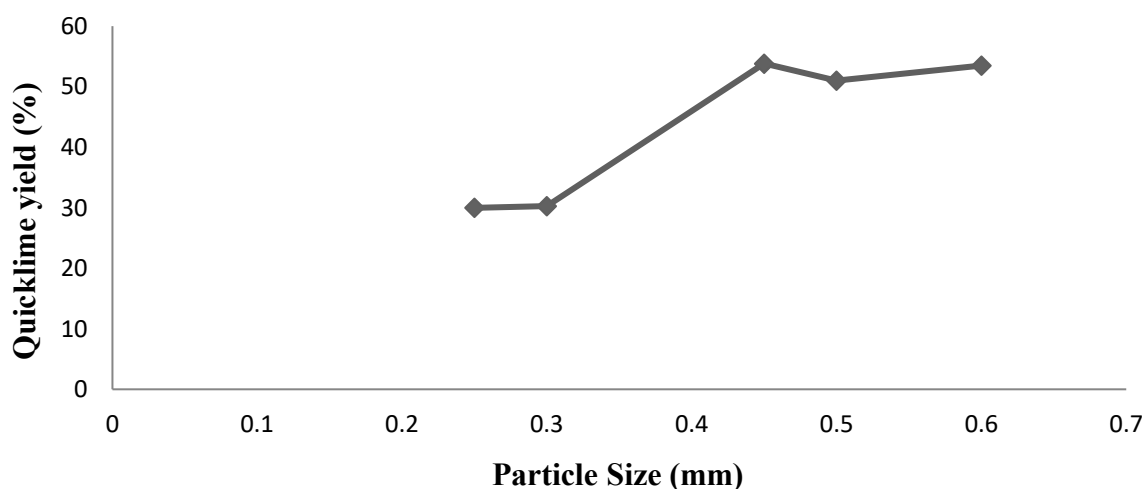


Figure 3. Effect of Particle Size on Quicklime Yield

This outcome can be explained by the interplay of heat and mass transfer phenomena. For larger particles ($>450\text{ }\mu\text{m}$), the lower surface-area-to-volume ratio impedes efficient heat penetration to the particle's core, resulting in incomplete calcination. Conversely, very fine particles ($<450\text{ }\mu\text{m}$) may lead to dense packing within the crucible, which can trap the evolving CO_2 gas, locally increasing the partial pressure and hindering the forward decomposition reaction. The $450\text{ }\mu\text{m}$ particle size, therefore, represents the optimal balance, allowing for rapid heat transfer while maintaining sufficient porosity for the CO_2 to escape efficiently.

In summary, the optimization study successfully identified the ideal conditions for energy-efficient quicklime production from this Nigerian biogenic waste: a calcination temperature of $900\text{ }^\circ\text{C}$, a duration of 60 minutes, and a particle size of $450\text{ }\mu\text{m}$. These parameters provide a practical blueprint for valorizing this waste stream in a manner that minimises energy consumption and maximises product yield.

5. CONCLUSION

This study addressed the dual challenge of industrial energy consumption and agricultural waste management in Nigeria by establishing an energy-efficient pathway for producing quicklime from a composite of local eggshell and snail shell waste. The research successfully determined the optimal calcination parameters required to maximize product yield while minimizing energy input.

The key findings demonstrate that the feedstock is a high-purity, viable alternative to quarried limestone. The optimal processing conditions were found to be a calcination temperature of $900\text{ }^\circ\text{C}$, a calcination time of 60 minutes, and a feedstock particle size of $450\text{ }\mu\text{m}$. Adhering to these parameters ensures the complete conversion of the biogenic waste to high-quality quicklime without the excessive energy consumption and material degradation associated with over-processing. These findings provide a practical, evidence-based blueprint for valorizing this common waste stream, contributing directly to the development of a circular economy and more sustainable industrial practices in Nigeria.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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UPGRADING A JATROPHA-BASED BIODIESEL PILOT PLANT IN NIGERIA: DESIGN AND COMMISSIONING OF A METHANOL RECOVERY CONDENSER

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ABSTRACT

Developing local renewable energy capacity is a strategic priority for Nigeria. However, the viability of small-scale biofuel production is often limited by process inefficiencies, such as the loss of volatile reactants. This paper addresses this challenge through the upgrading of a jatropha-based biodiesel pilot plant at Kaduna Polytechnic, Nigeria. The primary objective was to design, fabricate, and commission a condenser to recover vaporised methanol from the transesterification reactor. A shell-and-tube heat exchanger was designed using Aspen Exchanger Design & Rating (EDR) for a specified duty of condensing 125.6 kg/h of methanol. The design required a heat removal capacity of approximately 148 MJ/h and was successfully commissioned following local fabrication at a total cost of \$8,381. This study provides a complete, costed, and validated engineering blueprint for a practical process upgrade. It serves as a replicable case study for other institutions, demonstrating a feasible pathway for strengthening indigenous technical capacity and improving the sustainability of renewable energy research and production facilities in developing countries.

1. INTRODUCTION

Nigeria, like many developing nations, faces a significant energy deficit, relying heavily on fossil fuels while grappling with challenges of energy access and security (Olanrewaju et al., 2022). In response, transitioning to locally sourced renewable energy is a national strategic priority. Biodiesel produced from non-food feedstocks, such as *Jatropha curcas*, presents a promising decentralised energy solution that can support rural development and reduce carbon emissions (Ozoegwu et al., 2017). However, the success of small-scale biodiesel production hinges on process efficiency and economic viability.

A critical operational challenge in transesterification, the core process of biodiesel production, is the management of reactants. Methanol, a key reagent, is highly volatile and is typically heated to temperatures near its boiling point (65°C) during the reaction. Without an effective recovery system, significant amounts of vaporised methanol are lost to the atmosphere, increasing operational costs and introducing environmental and safety hazards. This issue is particularly acute in pilot-scale plants in research and educational institutions, where resource constraints can limit the initial design to essential components, deferring optimisation. The existing biodiesel pilot plant in the Chemical Engineering Department at Kaduna Polytechnic faced this precise limitation, lacking a condenser to capture and recycle vaporised methanol from the reactor.

While extensive literature exists on biodiesel chemistry, there is a scarcity of detailed, practical case studies on the retrofitting and technical upgrading of existing pilot plants in African institutional settings. This paper aims to fill that gap by documenting the complete engineering process of upgrading a jatropha-based biodiesel pilot plant through the design, fabrication, and commissioning of a shell-and-tube condenser for methanol recovery.

This study provides a comprehensive technical blueprint, including detailed design specifications generated using Aspen Exchanger Design & Rating V8.8, material and energy balances, and a full cost analysis for local fabrication. By presenting the results of the commissioning tests, this work offers a validated, practical guide for institutions seeking to enhance the efficiency and sustainability of their renewable energy facilities, thereby strengthening local capacity for biofuel research and production.

2. LITERATURE REVIEW

2.1 Biodiesel from *Jatropha curcas* as a Sustainable Feedstock

The global imperative to decarbonise the energy sector has intensified research into biofuels as a viable alternative to petroleum diesel. Biodiesel, a biodegradable and non-toxic fuel, is prominent among these alternatives due to its similar combustion properties and its potential to be produced from diverse feedstocks (El-Sattar et al., 2023). In developing countries like Nigeria, the focus has shifted towards non-edible, second-generation feedstocks to avoid competition with food crops. *Jatropha curcas* has been widely investigated for this purpose, as it can be cultivated on marginal lands, reducing the pressure on arable farmland (de Luna et al., 2022). However, realising the full potential of jatropha is contingent on overcoming challenges related to inconsistent yields and, crucially, developing efficient and cost-effective processing technologies suitable for local deployment (Mohammed et al., 2019).

2.2 Process Optimisation and the Imperative of Methanol Recovery

The economic feasibility of small- to medium-scale biodiesel production is highly sensitive to operational efficiency (Gebremariam & Marchetti, 2018). The transesterification process, while well-established, requires careful management of inputs to minimise costs. Methanol, used as a reactant, is a significant operational expense and a volatile organic compound. During the reaction, which is typically heated to 60–65°C, substantial quantities of methanol can be lost through vaporisation (Lee et al., 2015). Effective methanol recovery is therefore not merely an option but a critical step for process intensification and economic sustainability. As Singh et al. (2023) highlight, integrating recovery and recycling loops for excess methanol can improve the process mass intensity and reduce the overall environmental footprint, aligning with circular economy principles. A dedicated condenser is the primary unit operation for achieving this, converting the vaporised methanol back into a liquid state for reuse.

2.3 Simulation and Design of Biodiesel Production Systems

Modern process engineering relies heavily on simulation tools for designing, analysing, and optimising chemical plants before construction. Software packages like Aspen HYSYS and Aspen Exchanger Design & Rating (EDR) are industry standards for modelling reaction kinetics, performing material and energy balances, and sizing equipment such as reactors and heat exchangers (Sharma et al., 2020). These tools allow engineers to test various operating conditions and equipment designs virtually, saving significant time and resources. While many studies have employed these simulators to design new biodiesel plants from the ground up or to model entire process flowsheets (Tan et al., 2021), there is a notable gap in the literature. Specifically, there is a lack of published case studies that apply these powerful tools to the specific problem of retrofitting and upgrading existing, operational pilot plants in resource-constrained university settings within developing countries. Table 1, shown below, summarises key research, highlighting the gap this study addresses.

This review confirms that while the components of the problem—jatropha biodiesel, methanol recovery, and process simulation—are well-researched, their synthesis into a practical, documented case study of a pilot plant upgrade in Nigeria represents a novel and valuable contribution to the literature on sustainable energy development.

3. METHODOLOGY

3.1 Overview of the Biodiesel Pilot Plant

The research was conducted at the existing biodiesel pilot plant in the Chemical Engineering Department, Kaduna Polytechnic, Nigeria. The plant is designed to produce biodiesel from jatropha oil via a transesterification reaction using methanol and a sodium hydroxide catalyst. The process involves pre-heating the oil, mixing the catalyst with methanol, reacting the components in a jacketed reactor (R201) at approximately 65°C, and subsequent separation and purification steps. The primary limitation of the existing plant was the absence of a system to recover methanol that vaporised from the reactor, leading to material loss and economic inefficiency. The objective of this work was to remedy this by designing, fabricating, and incorporating a suitable condenser into the plant.

3.2 Condenser Design Basis and Specifications

The condenser upgrade was specified with a primary functional requirement: to condense 125.6 kg of methanol per batch. The design was developed for a shell-and-tube heat exchanger configuration. Key design and operating parameters were established as follows:

- *Design Pressure:* 3 bar for both shell and tube sides.
- *Design Temperature:* 100°C for the shell side, tube side, and tube sheets.
- *Corrosion Allowance:* 1.59 mm.
- *Number of Passes:* 1 for the shell side and 1 for the tube side.

3.3 Process Simulation and Detailed Equipment Design

The detailed design of the condenser was performed using *Aspen Exchanger Design & Rating (EDR) V8.8*. The software was used to conduct a complete process simulation to establish the material and energy balances required for the specified duty of condensing 125.6 kg/hr of methanol vapour. Based on the simulation results, the software was then used to perform the detailed equipment sizing and generate the final mechanical design specifications for the shell, tubes, and heads of the condenser. This process included determining the optimal number of tubes, tube diameter, tube length, and shell diameter to achieve the required heat transfer with the available cooling water utility.

Table 1. Review of Key Biodiesel Research and the Present Study's Angle

Reference	Methodology	Key Findings	Limitations / Gap	This Study's Angle
Sharma et al. (2020)	Aspen HYSYS simulation of a new biodiesel plant.	Provided a complete process model and economic analysis for a large-scale facility.	Theoretical design; does not address challenges of upgrading existing hardware.	Focuses on retrofitting an <i>existing</i> pilot plant.
Lee et al. (2015)	Economic analysis of different methanol recovery methods.	Showed that recovery via condensation and distillation is economically vital.	Primarily an economic model; lacks detailed engineering design or fabrication data.	Provides detailed engineering design, fabrication costs, and commissioning data.
Gebremariam & Marchetti (2018)	Review of biodiesel production economics.	Identified high feedstock and chemical costs as major barriers for small plants.	High-level review; does not offer a specific, actionable engineering solution.	Implements and documents a specific cost-saving engineering solution (condenser).
Mohammed et al. (2019)	Review of biofuel potential in Sub-Saharan Africa.	Highlighted a lack of local technical capacity and documented projects as barriers.	Policy and resource-level review.	Presents a hands-on, technical case study to help build local capacity.
Singh et al. (2023)	Review of process intensification techniques.	Stressed the importance of integrated designs for improving sustainability.	Conceptual review; does not detail the practical implementation of one technique.	Details the practical implementation of a key intensification step (methanol recovery).

3.4 Commissioning Protocol

Following fabrication based on the Aspen EDR design outputs, the new condenser was coupled with the existing biodiesel plant. The upgraded plant was then commissioned by conducting test runs for biodiesel production. The commissioning process involved operating the entire plant for three complete production cycles, designated as Batch A, Batch B, and Batch C. The performance of the condenser in cooling and liquefying the methanol vapour from the reactor was monitored during these batches to validate the design and ensure the upgraded system operated as intended.

4. RESULTS AND DISCUSSION

This section presents the results of the condenser design, including the material and energy balances, final equipment specifications, and a detailed cost analysis. The findings are discussed in the context of their practical implications for sustainable energy development at the local level.

4.1 Heat Duty and Process Balances

The primary design requirement was to condense 125.6 kg/h of methanol vapour produced during the transesterification reaction. Based on the process simulation in Aspen EDR, the required heat duty of the condenser was determined from the change in enthalpy of the methanol stream. The results of the energy balance are summarised in Table 2.

Table 2. Summary of Condenser Energy Flow and Calculated Heat Duty

Stream	Parameter	Value	Unit
Methanol In (Vapour)	Heat Flow	-782,179.34	kJ/h
Methanol Out (Liquid)	Heat Flow	-929,856.76	kJ/h
Calculated Heat Duty	(Heat Removed from Methanol)	147,677.42	kJ/h
Water In (Coolant)	Mass Flow	14,000	kg/h

The simulation established that a heat duty of approximately 148,000 kJ/h was required to be removed from the methanol vapour to achieve full condensation. This result formed the basis for the subsequent mechanical design and sizing of the shell-and-tube heat exchanger, ensuring it had sufficient surface area to handle the thermal load using the available cooling water supply.

4.2 Final Condenser Mechanical Design Specifications

The process simulation and sizing calculations in Aspen EDR produced a detailed mechanical design for a shell-and-tube heat exchanger, specified for local fabrication. Key design parameters are consolidated and summarised in Table 3.

Table 3. Final Mechanical Design Specifications for the Methanol Recovery Condenser

Component	Parameter	Value	Unit
Overall	TEMA Class	BEM	—
	Shell Inside Diameter	340	mm
	Number of Passes	1 (Shell) / 1 (Tube)	—
Tubes	Type	Plain	—
	Number of Tubes	35	—
	Outside Diameter (OD)	38.1	mm
	Wall Thickness	2.0	mm
	Length	700	mm

Pitch / Pattern	47.62 / 30°	mm / degree

The design features a compact unit with a total tube length of 700 mm and a shell diameter of 340 mm, making it suitable for integration into the existing pilot plant's limited space. The selection of standard tube dimensions (38.1 mm OD) and a straightforward single-pass configuration reflects a design optimised for ease of fabrication and maintenance using locally available materials and technical skills. This practical approach is critical for the long-term sustainability of research hardware in environments where access to specialised components and technicians may be limited, addressing a key barrier to technology adoption in the region noted by Mohammed et al. (2019).

4.3 Fabrication Cost Analysis

A detailed cost estimation was conducted based on the final design, covering materials, labour, and standard industrial mark-ups for a local fabrication workshop. The final estimated selling price for the complete, fabricated condenser was **\$8,381**. A breakdown of the major cost components is provided in Table 4.

Table 4. Summary of Estimated Condenser Fabrication Costs

Cost Item	Value	Unit / Rate	Total Cost (USD)
Material (excluding tubing)	–	–	\$2,227
Tubing Material	24.5	m @ \$5.2/m	\$129
Total Labour	77.31	hours @ \$60/hr	\$4,639
Mark-ups (Material & Labour)	10–20%	–	\$1,386
Total Selling Price			\$8,381

The analysis reveals that labour constituted the largest portion of the cost (approx. 55%), which is typical for custom fabrication projects in this context. The total cost of under \$8,400 demonstrates the economic feasibility of producing such essential chemical processing equipment locally, rather than relying on expensive imported alternatives. This finding directly addresses the economic barriers that often hinder the development of small-scale biodiesel facilities, as identified by Gebremariam & Marchetti (2018). By providing a transparent cost basis, this work serves as a valuable financial planning tool for other institutions aiming to undertake similar projects.

4.4 Commissioning and Discussion

The fabricated condenser was successfully installed and the upgraded pilot plant was commissioned over three complete biodiesel production batches. The thesis confirms that the unit operated as designed, successfully condensing the methanol vapour from the reactor. However, the source document does not provide quantitative performance data from the commissioning runs, such as the measured rate of methanol recovery or the outlet temperature of the condensate.

Despite the absence of quantitative performance metrics, the successful commissioning of a locally designed and fabricated piece of chemical processing equipment is a significant result. It validates the use of industry-standard simulation tools like Aspen EDR for developing robust designs tailored to local manufacturing capabilities. Furthermore, it represents a tangible step in building indigenous technical capacity for renewable energy infrastructure, a critical need across Sub-Saharan Africa. This practical achievement provides a counter-narrative to the common challenges of equipment failure and lack of maintenance, offering a replicable

blueprint for improving the efficiency and sustainability of educational and research-focused pilot plants.

5. CONCLUSION

This study successfully addressed a critical operational inefficiency in a jatropha-based biodiesel pilot plant by designing, fabricating, and commissioning a methanol recovery condenser. The work demonstrated the feasibility of using standard process simulation tools to engineer a shell-and-tube condenser tailored for local manufacturing. The final design was specified to condense 125.6 kg of methanol per batch, requiring a heat duty of approximately 148 MJ/h, and was fabricated locally for a total cost of \$8,381. The successful commissioning of the unit confirms the viability of this approach for upgrading existing renewable energy facilities.

The primary contribution of this paper is a practical and replicable engineering case study. It provides a transparent technical blueprint and cost analysis that can guide other educational and research institutions in Nigeria and beyond in enhancing their own biofuel production capabilities. This work underscores the value of combining modern design software with local fabrication to create sustainable and cost-effective solutions.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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RENEWABLE ENERGY-DRIVEN LIME CALCINATION: AN EMPIRICAL MODEL FOR PREDICTING QUICKLIME REACTIVITY BASED ON IRON II OXIDE COMPOSITION IN OBAJANA LIMESTONE TO SUPPORT SUSTAINABLE INDUSTRIAL DECARBONIZATION

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ABSTRACT

This study investigates the impact of Iron II Oxide (FeO) composition on the reactivity of quicklime produced from Obajana limestone, aiming to optimize lime calcination processes using renewable energy sources. The research objectives include characterizing the chemical composition of limestone samples, evaluating the effect of FeO content on quicklime reactivity, and developing an empirical model to predict reactivity based on FeO variations. Methodology involved X-ray Fluorescence (XRF) analysis for chemical characterization, controlled slaking experiments to assess reactivity, and statistical modeling to correlate FeO content with reactivity. Key findings indicate that higher FeO levels decrease quicklime reactivity, with reactivity declining from 0.0792 °C/s to 0.0097 °C/s for 0.25-mm particles and from 0.1304 °C/s to 0.0026 °C/s for 0.45-mm particles as FeO content increased from 0.0991% to 0.3258%. Exponential models provided the best fit for predictive accuracy, with R² values of 92.15% and 95.37% for 0.25-mm and 0.45-mm particles, respectively. These results underscore the importance of controlling impurity levels in sustainable lime production. The study's implications highlight the potential for integrating renewable energy-driven calcination systems to enhance energy efficiency and reduce carbon emissions, contributing to industrial decarbonization efforts.

1. INTRODUCTION

The production of quicklime (calcium oxide) is a critical industrial process with applications in various sectors, including construction, steel manufacturing, and environmental management (Boynton, 1980). Traditionally, lime calcination has been an energy-intensive process, predominantly reliant on fossil fuels, which contributes significantly to greenhouse gas emissions (Oates, 1998). As global efforts to mitigate climate change intensify, there is an urgent need to transition to more energy-efficient and renewable-energy-driven lime calcination processes.

Integrating renewable energy sources, such as solar thermal, biomass, and electrified kilns, into lime production can significantly reduce carbon emissions and enhance energy efficiency (Akande, 2015).

Despite the availability of high-grade limestone in Nigeria, the production of quicklime is often hampered by the presence of metallic impurities, particularly Iron II Oxide (FeO), which adversely affects the reactivity of the produced quicklime (Akande, 2015). Previous studies have highlighted the impact of impurities on lime quality but have not adequately addressed the specific relationship between FeO content and quicklime reactivity in the context of renewable energy-driven calcination (Moropoulou, Bakolas, & Aggelakopoulou, 2001). This study aims to fill this gap by developing an empirical model that correlates FeO composition in Obajana limestone with quicklime reactivity, thereby providing a predictive tool for optimizing calcination parameters under renewable energy conditions.

Empirical modeling plays a crucial role in understanding and predicting the behavior of complex systems. In this study, empirical models are employed to correlate the FeO content of Obajana limestone with the reactivity of the resulting quicklime. By using statistical techniques to analyze experimental data, the study develops robust models that can predict quicklime reactivity based on FeO variations. These models are essential for optimizing calcination processes, ensuring high-quality quicklime production, and minimizing energy waste (Montgomery, 2009). The validated models can be integrated into renewable energy-driven calcination systems, enabling precise control over process parameters and enhancing overall energy efficiency.

This research aligns with global trends in industrial decarbonization and the United Nations Sustainable Development Goals (SDGs). Specifically, it supports SDG 7 (Affordable and Clean Energy) by promoting the use of renewable energy in lime production, SDG 9 (Industry, Innovation, and Infrastructure) by fostering innovation in industrial processes, and SDG 13 (Climate Action) by reducing carbon emissions through optimized energy use. By addressing the challenges associated with traditional lime calcination and proposing sustainable solutions, this study contributes to the broader goal of achieving a low-carbon, sustainable industrial future.

2. LITERATURE REVIEW

2.1 Renewable Energy Applications in Lime Calcination

The integration of renewable energy sources into lime calcination processes is a growing area of interest, driven by the need to reduce carbon emissions and enhance energy efficiency. Traditional lime calcination relies heavily on fossil fuels, contributing significantly to greenhouse gas emissions (Oates, 1998). Renewable energy sources such as solar thermal, biomass, and electrified kilns offer promising alternatives. Solar thermal energy, for instance, can provide the high temperatures required for calcination, while biomass can serve as a carbon-neutral fuel source (Akande, 2015). Electrified kilns, powered by renewable electricity, also present a viable option for sustainable lime production. The adoption of these technologies not only aligns with global decarbonization goals but also supports the transition to a circular economy by utilizing waste materials as energy sources.

2.2 Factors Influencing Quicklime Reactivity

Quicklime reactivity is a critical parameter in determining the quality and usability of the final product. Several factors influence quicklime reactivity, including the chemical composition of

the limestone, calcination temperature, particle size, and the presence of impurities (Boynton, 1980). The specific surface area and porosity of the quicklime also play significant roles. Higher calcination temperatures can lead to sintering, which reduces the surface area and reactivity of the quicklime (Moropoulou, Bakolas, & Aggelakopoulou, 2001). The presence of impurities, particularly metallic oxides such as Iron II Oxide (FeO), can adversely affect the reactivity by altering the microstructural properties of the calcined product (Akande, 2015).

2.3 Empirical Models and Predictive Methodologies Used in Lime Calcination

Empirical modeling is a valuable tool for predicting the behavior of complex systems, such as lime calcination. These models use statistical techniques to analyze experimental data and develop correlations between various parameters. In the context of lime calcination, empirical models can predict quicklime reactivity based on factors such as chemical composition, calcination temperature, and particle size (Montgomery, 2009). Common modeling approaches include linear regression, polynomial regression, and exponential models. These models are essential for optimizing calcination processes, ensuring consistent product quality, and minimizing energy consumption. The development of robust empirical models can also facilitate the integration of renewable energy sources by providing predictive insights into process performance under variable energy inputs.

2.4 The Role of Iron II Oxide Composition in Limestone and Its Impact on Quicklime Quality

Iron II Oxide (FeO) is a common impurity in limestone that can significantly impact the quality of quicklime. Higher FeO content in limestone can lead to the formation of low-reactivity quicklime, which is less effective in industrial applications (Akande, 2015). The presence of FeO affects the thermal decomposition of calcium carbonate (CaCO_3) during calcination, leading to changes in the microstructure and reactivity of the quicklime (Moropoulou et al., 2001). Understanding the relationship between FeO content and quicklime reactivity is crucial for optimizing lime production processes. This study aims to develop an empirical model that correlates FeO composition in Obajana limestone with quicklime reactivity, providing a predictive tool for improving product quality and process efficiency.

2.5 Theoretical Frameworks, Past Empirical Studies, and Research Gaps

The theoretical framework for this study is grounded in the principles of chemical kinetics and thermodynamics, which govern the calcination process and the reactivity of quicklime. Past empirical studies have explored various aspects of lime production, including the effects of calcination temperature, particle size, and impurities on quicklime quality (Boynton, 1980; Moropoulou et al., 2001). However, there is a lack of comprehensive studies that specifically address the impact of FeO composition on quicklime reactivity in the context of renewable energy-driven calcination. This research aims to fill this gap by developing and validating an empirical model that can predict quicklime reactivity based on FeO content, thereby supporting the transition to sustainable lime production practices.

3. METHODOLOGY

3.1 Research Design

This study employs an experimental research design to investigate the impact of Iron II Oxide (FeO) composition on the reactivity of quicklime produced from Obajana limestone. The research involves the collection of limestone samples, chemical analysis using X-ray Fluorescence (XRF), calcination using renewable energy sources, slaking experiments to assess quicklime reactivity, and empirical modeling to predict reactivity based on FeO composition.

3.2 Materials and Equipment

The primary materials used in this study include Obajana limestone samples collected from multiple points within the Obajana quarry. The key equipment utilized are:

- *X-ray Fluorescence (XRF) Analyzer*: For determining the chemical composition of limestone samples.
- *Kiln Setup*: For the calcination process, simulating renewable energy sources such as solar thermal and biomass.
- *Slaking Reactor*: For conducting slaking experiments to measure quicklime reactivity.
- *Electronic Weighing Balance*: For precise measurement of sample weights.
- *Mechanical Sieve Agitator*: For particle size reduction and separation.
- *Carbolite Furnace*: For controlled heating during the calcination process.

3.3 Experimental Procedures

3.3.1 Sample Collection

Limestone samples were collected from ten different points within the Obajana limestone quarry, located in Kogi State, Nigeria. The samples were chosen to represent a range of FeO compositions and were collected at intervals of 10 meters to ensure variability.

3.3.2 Chemical Analysis

The chemical composition of the limestone samples was determined using X-ray Fluorescence (XRF) analysis. The samples were prepared by mixing 1 g of limestone with 7 g of lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$) flux in a platinum crucible. The mixture was fused in a fusion machine, and the resulting disk was analyzed using the XRF analyzer to determine the FeO content and other elemental compositions.

3.3.3 Calcination Process

The calcination process was conducted using a Carbolite furnace, simulating renewable energy sources. Approximately 30 g of limestone sample (particle size 250 μm and 450 μm) was placed in a crucible and heated to 901°C for 60 minutes. The calcined samples were then cooled in a desiccator containing silica gel to prevent moisture absorption.

3.3.4 Slaking Experiments

The reactivity of the calcined quicklime was assessed through slaking experiments, following the ASTM C110 standard. The calcined limestone was weighed, and deionized distilled water (four times the weight of the limestone) was added to a slaking reactor with a stirrer set at 400 rpm. The temperature was recorded at 30-second intervals until no further change was observed. The reactivity (R) was calculated using the formula:

$$R = \Delta T_m \Delta t R = \Delta t \Delta T_m$$

where ΔT_m is the difference between the maximum and minimum temperatures, and Δt is the time to reach the maximum temperature.

3.4 Data Acquisition for Empirical Modeling

Data from the slaking experiments, including FeO composition and quicklime reactivity, were collected and used to develop empirical models. The models aimed to predict quicklime reactivity based on FeO content.

3.5 Empirical Modeling Approach

Empirical models, including linear, exponential, power, polynomial, and logarithmic formulations, were developed to correlate quicklime reactivity with FeO content. The models were evaluated based on the coefficient of determination (R^2) to identify the best fit. Statistical precision analyses, including correlation coefficients, covariance, and standard error, were conducted to validate the models.

4. RESULTS AND DISCUSSION

This section presents the key findings from the experimental work described in Chapter Four, including (a) the chemical composition of Obajana limestone and its Iron II Oxide variations, (b) the effect of Iron II Oxide content on quicklime reactivity, and (c) the development and statistical validation of an empirical model correlating these parameters. Graphical representations (Figures 1–14) and tabulated kinetic parameters (Tables 1, 2, 3, 4, and 5) support these findings. The discussion further compares these results with previous studies and explores implications for sustainable lime production while highlighting challenges, limitations, and avenues for future research.

4.1. Chemical Composition of Limestone Samples

X-ray Fluorescence (XRF) analysis was employed to characterize the chemical composition of limestone samples collected from various locations within the Obajana quarry. As shown in Table 1, the Iron II Oxide content varied significantly—from 0.0982% to 0.8336%—over a 90-m span. Despite these variations, the predominant compound in all samples was calcium carbonate (CaCO_3), primarily present as calcium oxide (CaO). The measured Iron II Oxide levels are comparable to those reported for commercial and regional limestones, confirming that the Obajana limestone is of high grade and suitable for commercial quicklime production (Akande, 2015).

Table 1. Percentage Iron II Oxide Composition of Obajana Limestone Using XRF

Sample No	Distance Apart of the Limestone Location (m)	Limestone Calcium Oxide Composition (%)	Limestone Iron III Oxide Composition (%)	Limestone Magnesium Oxide Composition (%)	Limestone Silica Composition (%)
1	0	53.3510	0.0991	0.0982	0.1562
2	10	53.1084	0.1024	0.1495	0.2175
3	20	53.0447	0.1026	0.2881	0.2923
4	30	52.7101	0.1271	0.4079	1.0876
5	40	52.3409	0.1369	0.4751	1.2720
6	50	51.1742	0.1812	0.4825	2.5742
7	60	51.0101	0.2319	0.5002	2.6007
8	70	50.5871	0.2561	0.7496	3.1363
9	80	50.3373	0.2634	0.8156	3.9196
10	90	50.0333	0.3258	0.8336	4.8054

The results indicate that the predominant compound in the limestone samples is calcium carbonate (CaCO_3), primarily present as calcium oxide (CaO). The Iron II Oxide levels are comparable to those reported for commercial and regional limestones, confirming that the

Obajana limestone is of high grade and suitable for commercial quicklime production (Akande, 2015).

4.2 Impact of Iron II Oxide Composition on Quicklime Reactivity

The reactivity of quicklime produced from Obajana limestone was evaluated by subjecting calcined samples to controlled slaking experiments. Figures 1 and 2 illustrate that quicklime reactivity decreases as the Iron II Oxide composition increases. For the 0.25-mm particle size, reactivity declined from 0.0792 °C/s to 0.0097 °C/s as Iron II Oxide increased from 0.0991% to 0.3258%. A similar trend was observed for the 0.45-mm particle size, where reactivity dropped from 0.1304 °C/s to 0.0026 °C/s over the same compositional range. These results suggest that higher levels of Iron II Oxide adversely affect the thermal response during the slaking process, likely due to impurity-induced alterations in the microstructural properties of the calcined product (Akande, 2015; Moropoulou, Bakolas, & Aggelakopoulou, 2001).

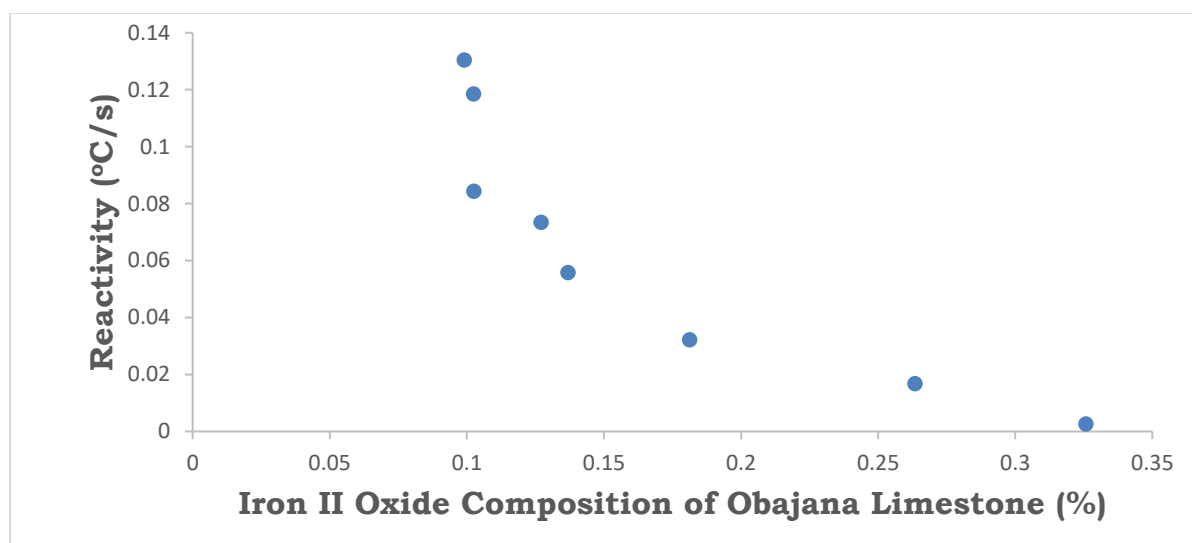


Figure 1. Effect of Iron II Oxide Composition of Obajana Limestone on Quicklime Reactivity for Limestone Particle Size of 0.25 mm

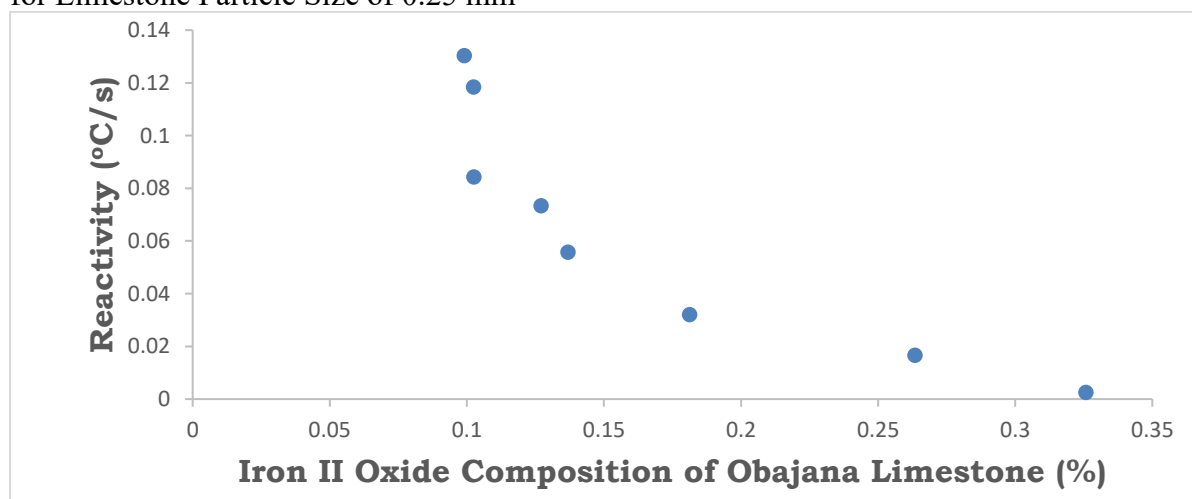


Figure 2. Effect of Iron II Oxide Composition of Obajana Limestone on Quicklime Reactivity for Limestone Particle Size of 0.45 mm

4.3 Empirical Modeling and Statistical Validation

A series of empirical models—including linear, exponential, power, polynomial, and logarithmic formulations—were applied to correlate quicklime reactivity with the Iron II Oxide

content of Obajana limestone. For the 0.25-mm particle size, the exponential model emerged as the best fit, achieving a coefficient of determination (R^2) of 92.15% (see Table 2 and Figures 4.3–4.7). Similarly, for the 0.45-mm fraction, the exponential model provided the highest R^2 of 95.37% (see Table 3 and Figures 8–12). Statistical precision analyses yielded a correlation coefficient of 0.7029 (adjusted $R^2 = 0.494$) and low covariance (0.00359) and standard error (0.019) for the 0.25-mm particles, while the 0.45-mm model displayed a correlation coefficient of 0.6718 (adjusted $R^2 = 0.451$), covariance of 0.00638, and standard error of 0.038 (Tables 4 and 5). Moreover, Figures 13 and 14 demonstrate a close agreement between experimental observations and model predictions, confirming the model's robustness (Doddapaneni et al., 2007; Montgomery, 2009).

Table 2. Coefficient of Determination (R^2) for Different Empirical Models for 0.25 mm Limestone Particle Size

Model Type	Model Equation	R^2
Linear	$y = 0.2234x + 0.0756$	0.6902
Polynomial	$y = 1.6012x^2 - 0.8842 + 0.1313$	0.8008
Exponential	$y = 0.1167e^{-7.748x}$	0.9214
Logarithmic	$y = 0.044\ln(x) - 0.0445$	0.7709
Power	$y = 0.002x^{-1.457}$	0.9431

Table 3. Coefficient of Determination (R^2) for Different Empirical Models for 0.45 mm Limestone Particle Size

Model Type	Model Equation	R^2
Linear	$y = 0.4801x + 0.1449$	0.7914
Polynomial	$y = 2.563x^2 - 1.5183 + 0.2327$	0.8747
Exponential	$y = 0.4721e^{-14.13x}$	0.9035
Logarithmic	$y = 0.092\ln(x) - 0.1076$	0.8649
Power	$0.0004x^{-2.496}$	0.8426

Figures 3–7: Empirical Models for 0.25 mm Limestone Particle Size

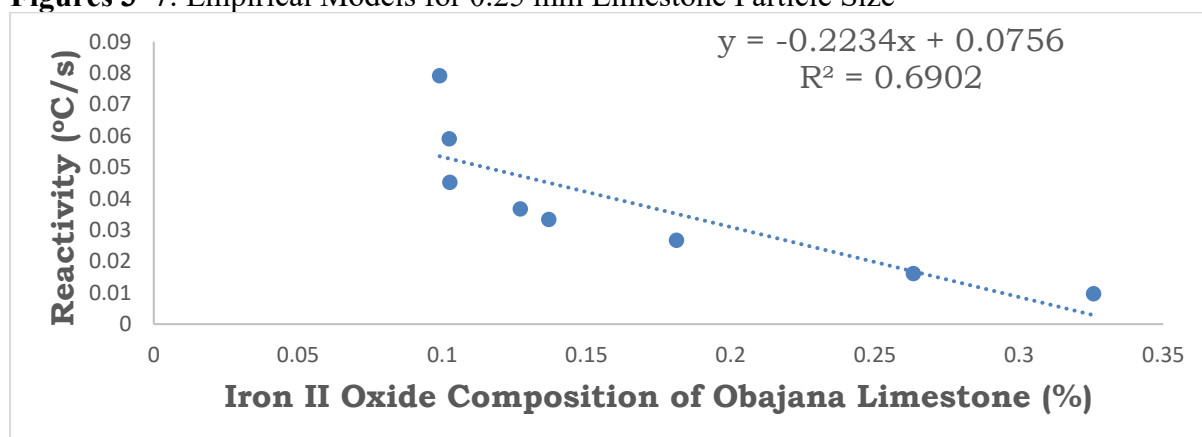


Figure 3. Linear Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.25 mm

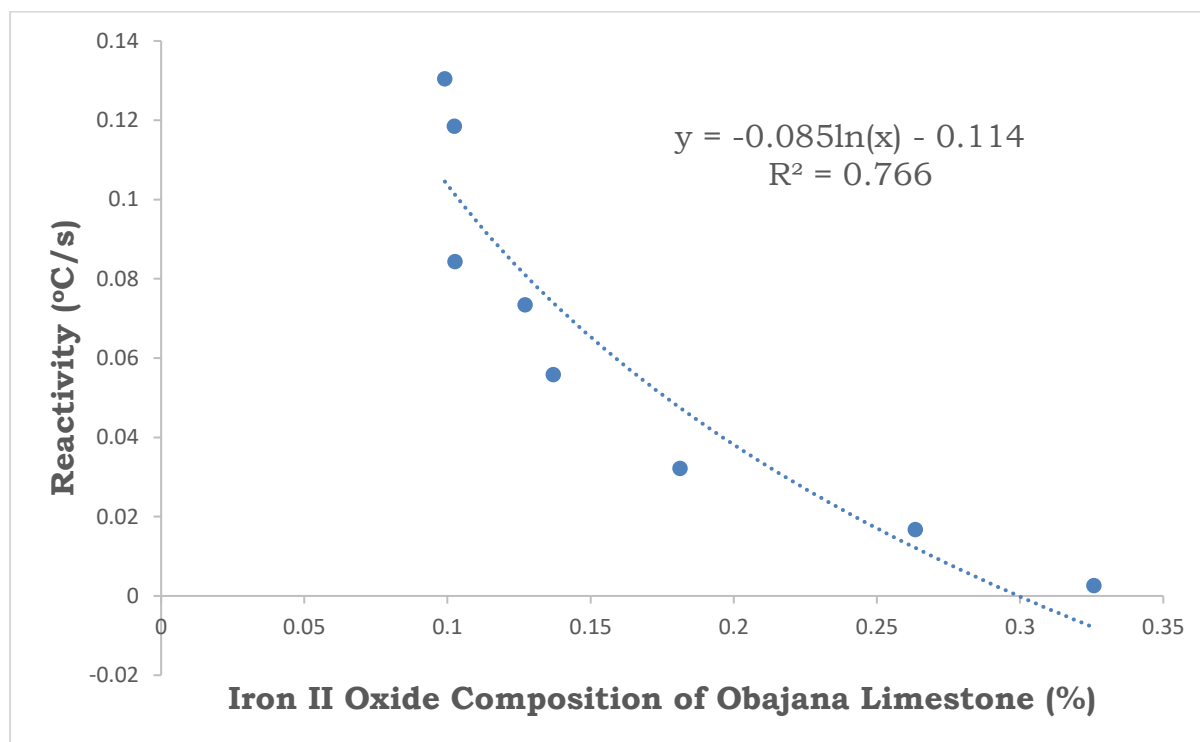


Figure 4. Logarithmic Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.25 mm.

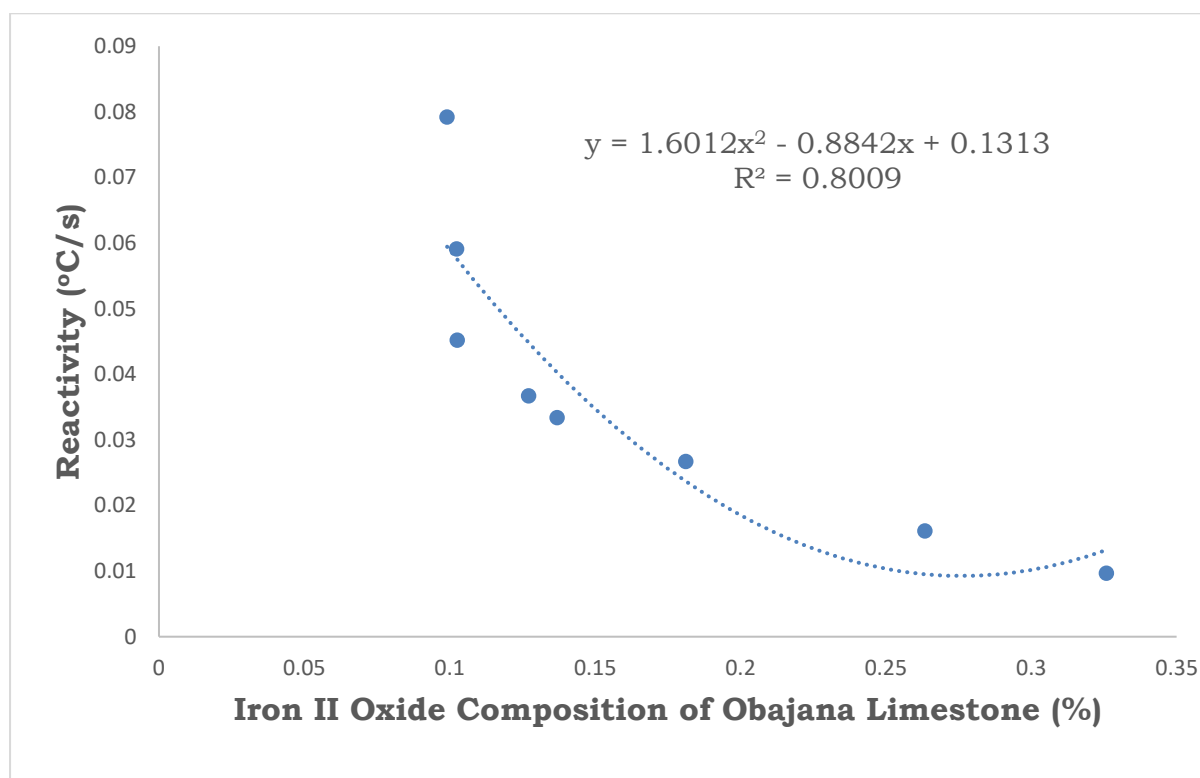


Figure 5. Polynomial Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.25 mm.

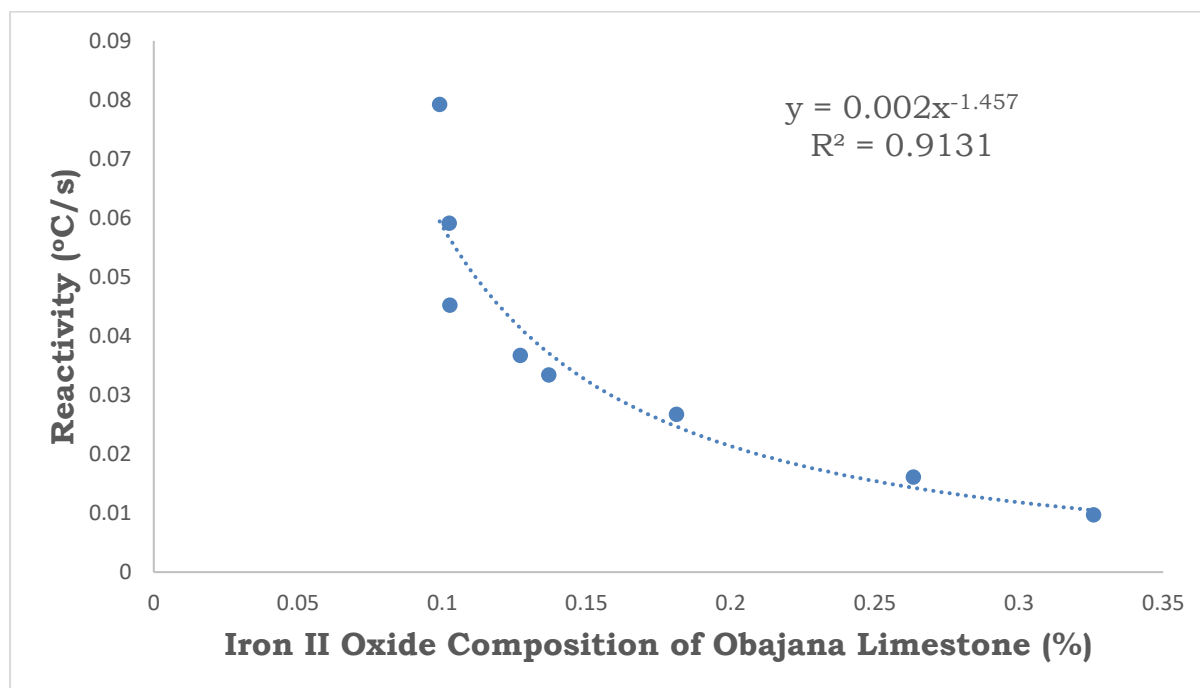


Figure 6. Power Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.25 mm.

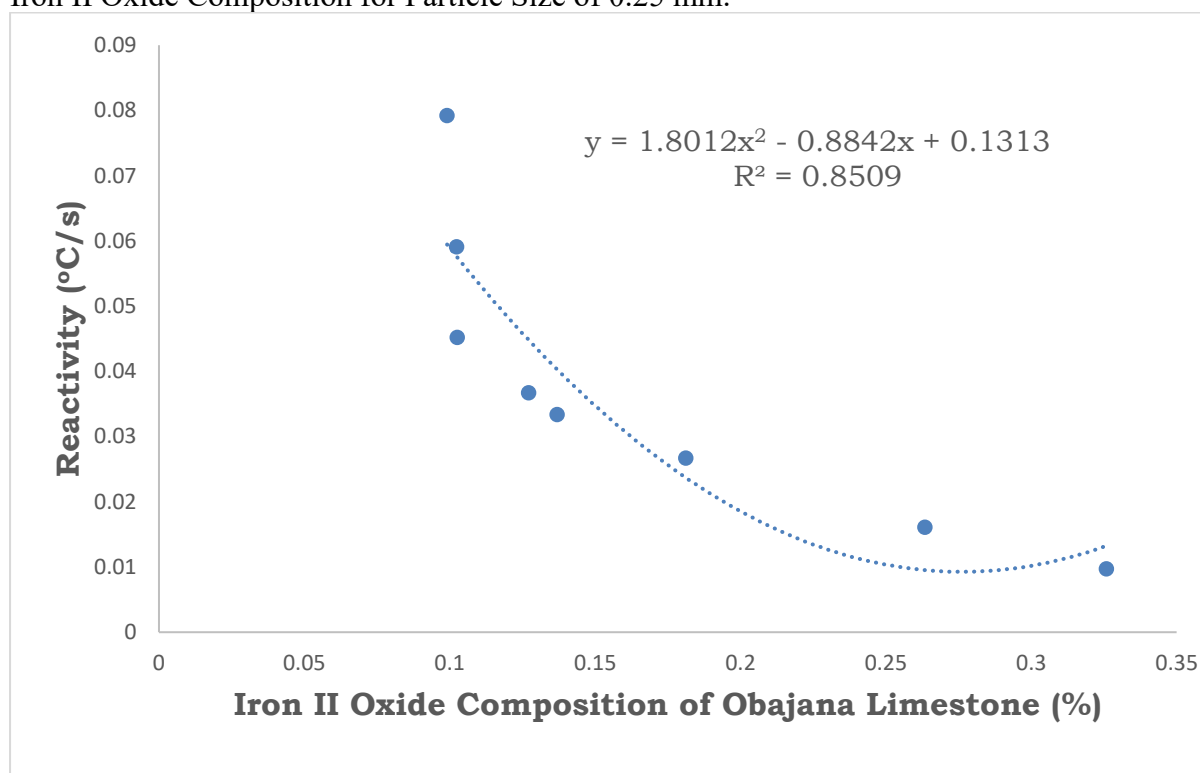


Figure 7. Exponential Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.25 mm

Figures 8–12: Empirical Models for 0.45 mm Limestone Particle Size

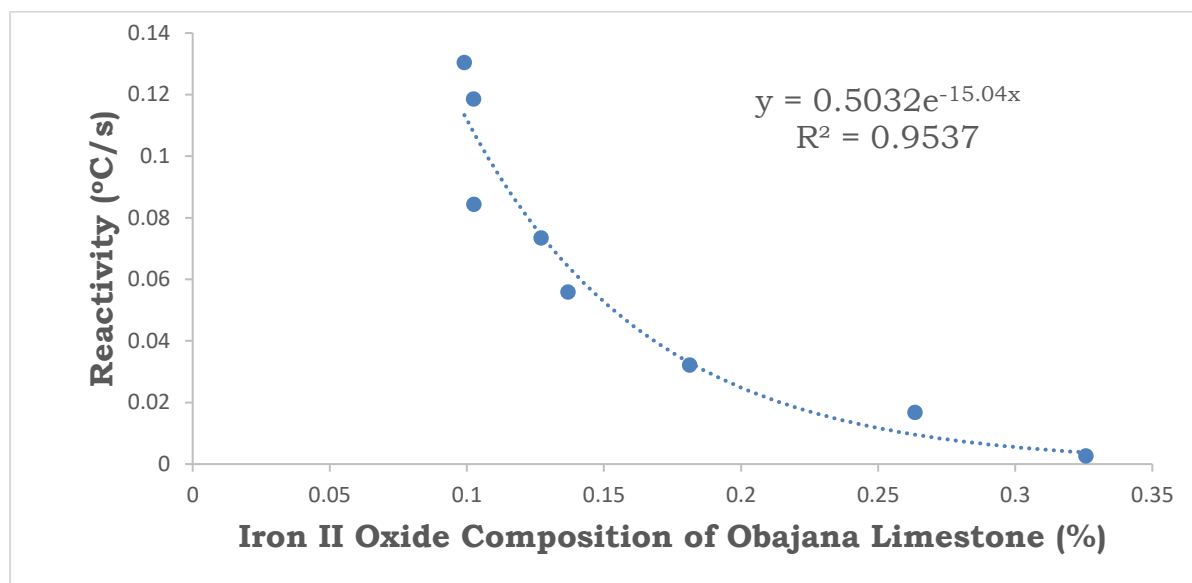


Figure 8. Exponential Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.45 mm

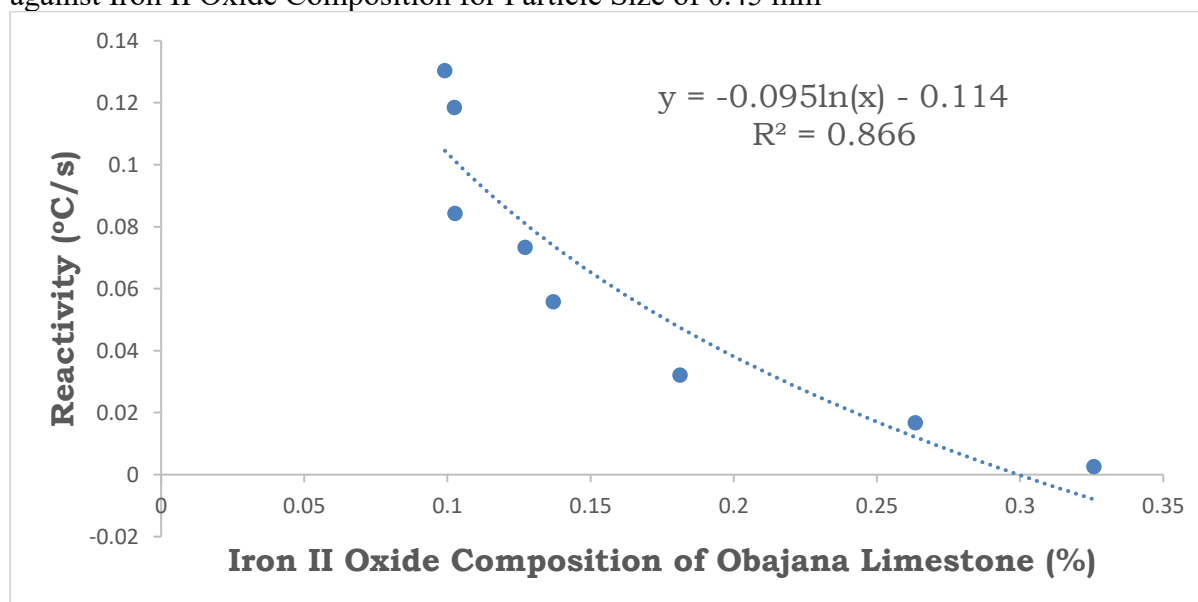


Figure 9. Logarithmic Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.45 mm

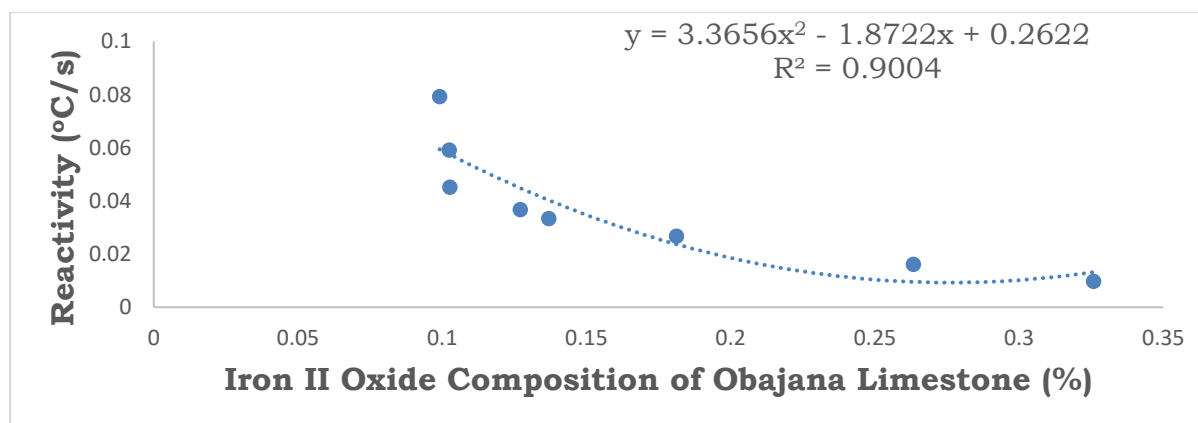


Figure 10. Polynomial Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.45 mm

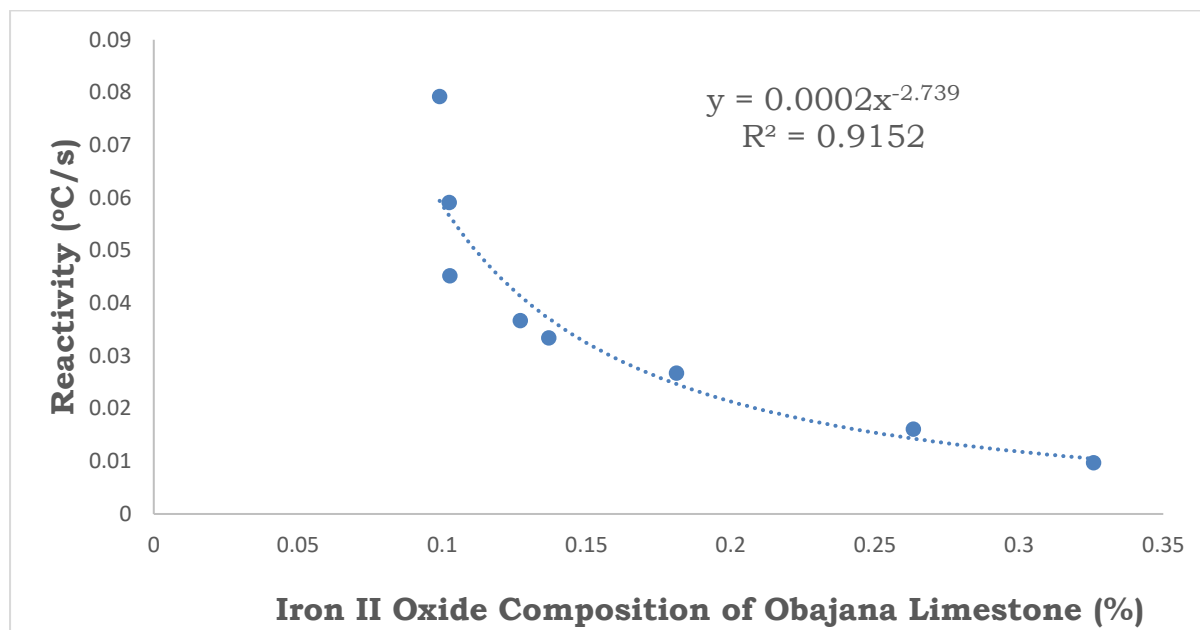


Figure 11. Power Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.45 mm.

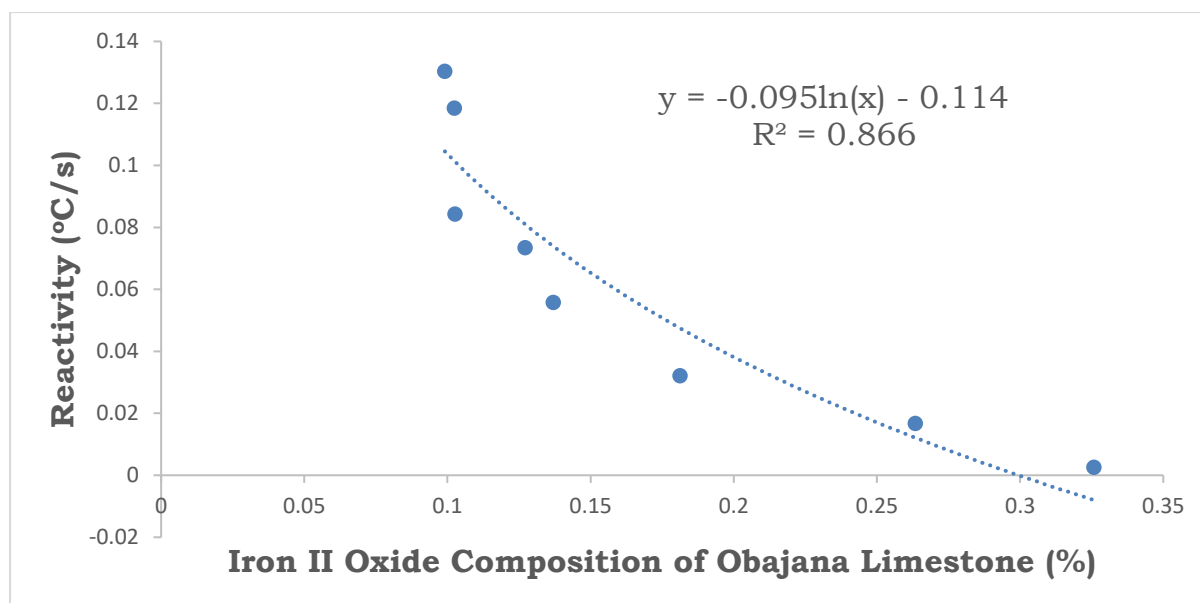


Figure 12. Linear Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.45 mm

Table 5. Statistical Precision Analysis for Comparing the Experimental to the Simulated Results for Quicklime Reactivity against Composition for Particle Size of 0.25 mm

Statistical Parameters	Value
Correlation Coefficient	0.7029
Adjusted Correlation Coefficient	0.494
Covariance	0.00359
Standard Error	0.019
Standard Deviation	0.189
Variance	0.036

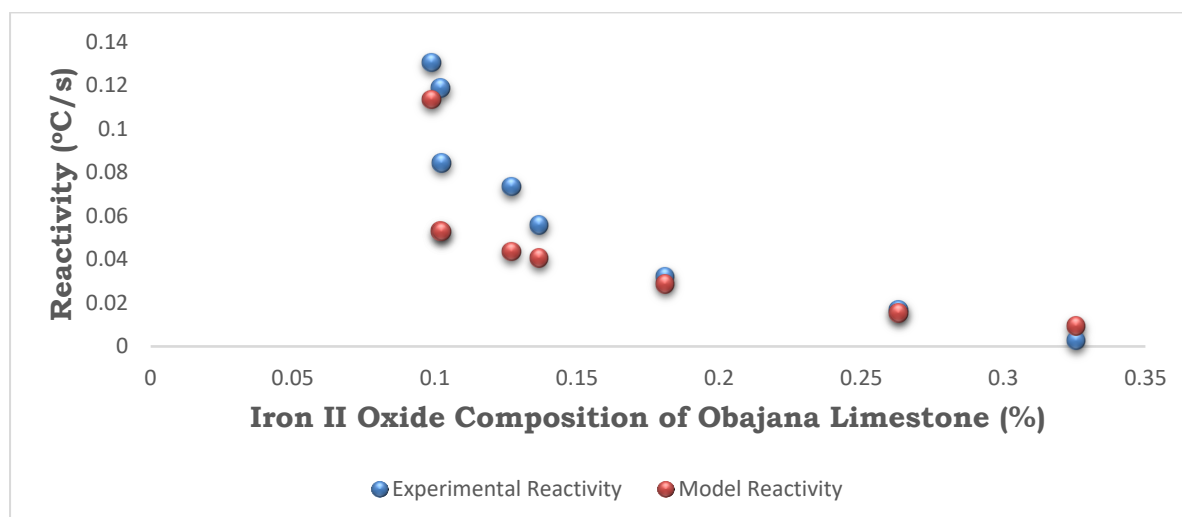


Figure 13. Exponential Model of Obajana Limestone Showing the Variation of its Experimental and Model Quicklime Reactivity against Iron II Oxide Composition for Particle Size of 0.25 mm

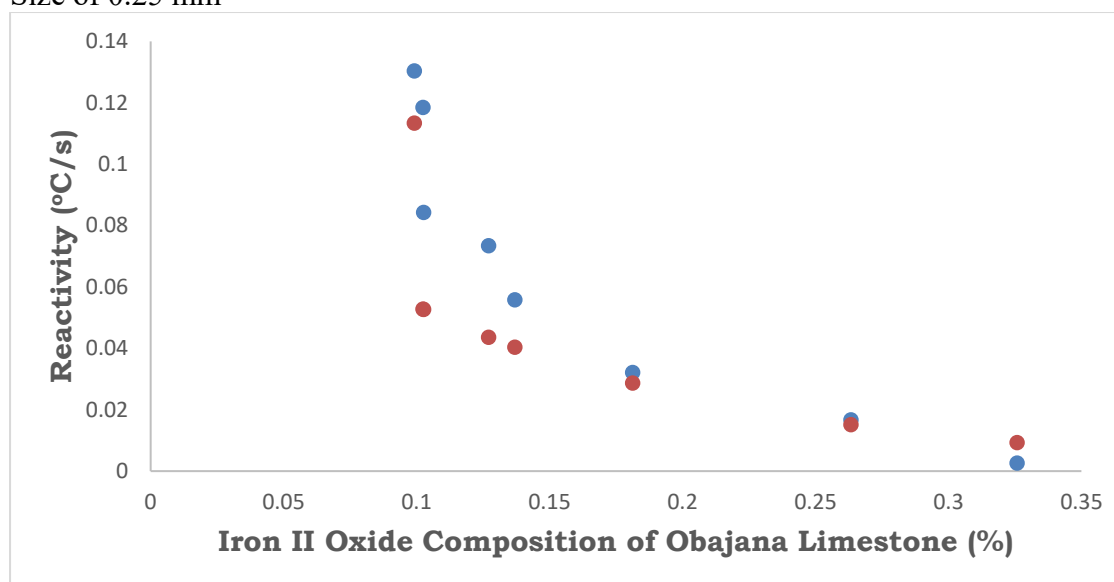


Figure 14: Exponential Model of Obajana Limestone Showing the Variation of its Experimental and Model Quicklime Reactivity against Iron II Oxide Composition for Particle Size of 0.45 mm

4.4. Comparison with Previous Studies and Implications for Sustainable Lime Production

The inverse relationship between Iron II Oxide content and quicklime reactivity observed in this study is consistent with earlier findings, which report that metallic impurities adversely affect the calcination process and the resultant reactivity of quicklime (Akande, 2015; Moropoulou et al., 2001). The decrease in reactivity with increasing Iron II Oxide suggests that controlling impurity levels is critical for optimizing calcination and slaking processes. Integrating the validated exponential model into renewable energy-driven calcination systems could enable more precise control over process parameters, thereby enhancing energy efficiency and reducing carbon emissions. This approach is particularly relevant for sustainable industrial decarbonization strategies, as it facilitates the production of high-quality quicklime with lower energy consumption.

4.5. Challenges, Limitations, and Future Research Directions

While the developed exponential model demonstrates robust predictive capability within the defined experimental domain, several challenges and limitations should be noted. The current model is based on a specific range of particle sizes (0.25 mm and 0.45 mm) and Iron II Oxide compositions. Variability in other process parameters—such as slaking water type, water temperature, and stirring speed—was not addressed and could influence reactivity outcomes. Future research should incorporate advanced characterization techniques (e.g., X-ray diffraction, scanning electron microscopy) to develop more comprehensive models. Additionally, exploring the effects of different renewable energy sources on the calcination process could further optimize sustainable calcination processes.

5. CONCLUSION

This study has demonstrated the significant impact of Iron II Oxide (FeO) composition on the reactivity of quicklime produced from Obajana limestone. Key findings indicate that higher FeO levels decrease quicklime reactivity, with reactivity declining from 0.0792 °C/s to 0.0097 °C/s for 0.25-mm particles and from 0.1304 °C/s to 0.0026 °C/s for 0.45-mm particles as FeO content increased from 0.0991% to 0.3258%. The developed empirical models, particularly the exponential model, provided robust predictive capabilities with R^2 values of 92.15% and 95.37% for 0.25-mm and 0.45-mm particles, respectively. These results underscore the importance of controlling impurity levels in sustainable lime production. The study contributes to the field of sustainable industrial decarbonization by providing a pathway to optimize lime calcination processes using renewable energy sources, thereby enhancing energy efficiency and reducing carbon emissions. Future research should explore advanced characterization techniques and the effects of different renewable energy sources on the calcination process to further optimize sustainable lime production.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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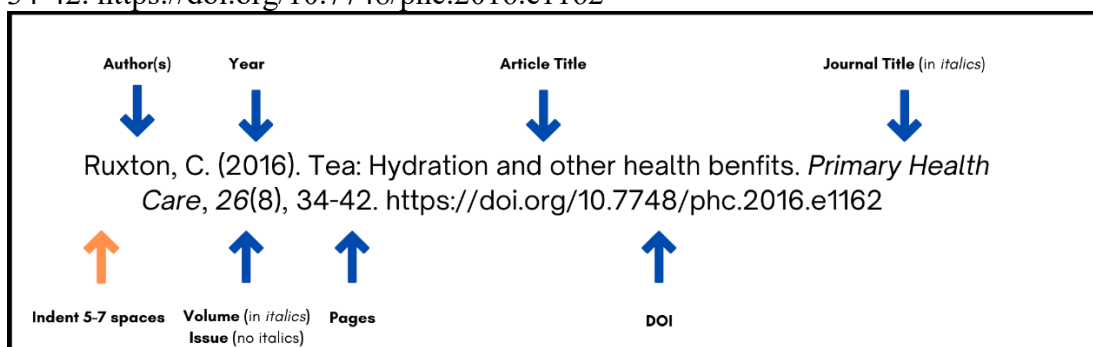
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Example:

Ruxton, C. (2016). Tea: Hydration and other health benefits. *Primary Health Care*, 26(8), pp. 34-42. <https://doi.org/10.7748/phc.2016.e1162>



Material Type	In-Text Example	Reference List Example
Journal Article: Single author	"Black tea is the second most consumed beverage in the world after water" (Ruxton, 2016, p. 34). OR Ruxton (2016) suggests "Unsweetened tea can be part of a recommended diet" (p. 40). Include page numbers for direct quotes.	Ruxton, C. (2016). Tea: Hydration and other health benefits. <i>Primary Health Care</i>, 26(8), pp. 34-42. https://doi.org/10.7748/phc.2016.e1162 Where a DOI is available it must be included at the end of the reference, in the format https://doi.org/10.xxxx
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Journal Article: 21 or more authors	Research indicated that "lost sense of smell is a factor" (Khan <i>et al.</i>, 2017, p. 344). OR Khan et al. (2019) used criteria which included "reduced or lost sense of smell" (p. 344). Cite only the surname of the first author followed by <i>et al.</i> and the year. Include page numbers for direct quotes.	Khan, A., Huynh, T. M. T., Vandeplas, G., Joish, V. N., Mannent, L. P., Tomassen P., van Zele, T., Cardell, L.O., Arebro, J., Olze, H., Forster-Ruhrmann, U., Kowalski, M. L., Olszewska-Ziaber, A., Fokkens, W., van Drunen, C., Mullol, J., Alobid, I., Hellings, P.W., Hox, V., ...Bachert, C. (2019). The GALEN rhinosinusitis cohort: Chronic rhinosinusitis with nasal polyps affects health-related quality of life. <i>Rhinology</i>, 57(5), pp. 343-351. https://doi.org/10.4193/Rhin19.158 Provide the names of the first 19 authors, insert an ellipsis [...] (but no ampersand [&]), then add the final author's name.
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Journal Article from the Cochrane Database of Systematic Reviews	The review included 78 trials employing a variety of intervention approaches (Hodder et al., 2019).	Hodder, R. K., O'Brien, K. M., Stacey, F. G., Tzelepis, F., Wyse, R. J., Bartlem, K. M., Sutherland, R., James, E. L., Barnes, C., & Wolfenden, L. (2019). Interventions for increasing fruit and vegetable consumption in children aged five years and

	OR Hodder <i>et al.</i> (2019) identified 78 relevant trials that employed a variety of intervention approaches.	under. <i>Cochrane Database of Systematic Reviews</i>. https://doi.org/10.1002/14651858.CD008552.pub6 Articles in the Cochrane Database of Systematic Reviews can only be retrieved from this database, therefore the name of the database (in italics) is included as the source of the article.
Online Journal Article: No DOI (With an Article Number)	Marion <i>et al.</i> (2018) explore whether evil characters in film share .. OR .. including stereotypical depictions of evil characters in film (Marion <i>et al.</i>, 2018).	Marion, T., Reese, V., & Wagner, R. F. (2018). Dermatologic features in good film characters who turn evil: The transformation. <i>Dermatology Online Journal</i>, 24(9), Article 4. https://escholarship.org/uc/item/1666h4z5 For an online journal article with no DOI (other than those retrieved from a Library database), provide the direct URL for the article. For journal issues with article numbers (rather than consecutive pagination) replace with page numbers with the word 'Article' followed by the article number or eLocator.
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Online Journal Article: No page numbers	.. in all outcomes (Christensen <i>et al.</i>, 2019). OR Christensen <i>et al.</i> (2019) examine .. For direct quotes of online material without pagination, name the sections and paragraph number: The authors' "objective was to identify control journals that did not require data posting" (Christensen <i>et al.</i>, 2019, Broad Analysis section, para. 4).	Christensen, G., Dafoe, A., Miguel, E., Moore, D. A., & Rose, A. K. (2019). A study of the impact of data sharing on article citations using journal policies as a natural experiment. <i>PLoS ONE</i>, 14(2), Article e0225883. https://doi.org/10.1371/journal.pone.0225883

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A few researchers in the linguistics field have developed training programs designed to improve native speakers' ability to understand accented speech (Derwing et al., 2002; Thomas, 2004). Their training techniques are based on the research described above indicating that comprehension improves with exposure to non-native speech. Derwing et al. (2002) conducted their training with students preparing to be social workers, but note that other professionals who work with non-native speakers could benefit from a similar program.

References

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- Thomas, H. K. (2004). *Training strategies for improving listeners' comprehension of foreign-accented speech* (Doctoral dissertation). University of Colorado, Boulder.

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Asmelash, L. (2019, August 14). *Social media use may harm teens' mental health by disrupting positive activities, study says*. CNN. <https://www.cnn.com/2019/08/13/health/social-media-mental-health-trnd/index.html>

Web page with organizational author:

In-text citation

More than 300 million people worldwide are affected by depression (World Health Organization, 2018).

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World Health Organization. (2018, March 22). *Depression*. <https://www.who.int/en/news-room/fact-sheets/detail/depression>

Web page with no date:

In-text citation

Establishing regular routines, such as exercise, can help survivors of disasters recover from trauma (American Psychological Association [APA], n.d.).

Reference entry

American Psychological Association. (n.d.). *Recovering emotionally from disaster*. <http://www.apa.org/helpcenter/recovering-disasters.aspx>

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Author's name in parentheses:

One study found that the most important element in comprehending non-native speech is familiarity with the topic (Gass & Varonis, 1984).

Author's name part of narrative:

Gass & Varonis (1984) found that the most important element in comprehending non-native speech is familiarity with the topic.

Group as author:

First citation: (American Psychological Association [APA], 2015)

Subsequent citation: (APA, 2015)

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Direct quote: (include page number and place quotation marks around the direct quote)

One study found that “the listener's familiarity with the topic of discourse greatly facilitates the interpretation of the entire message” (Gass & Varonis, 1984, p. 85).

Gass & Varonis (1984) found that “the listener’s familiarity with the topic of discourse greatly facilitates the interpretation of the entire message” (p. 85).

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This suggests that familiarity with nonnative speech in general, although it is clearly not as important a variable as topic familiarity, may indeed have some effect. That is, prior experience with nonnative speech, such as that gained by listening to the reading, facilitates comprehension. (Gass & Varonis, 1984, p. 77)

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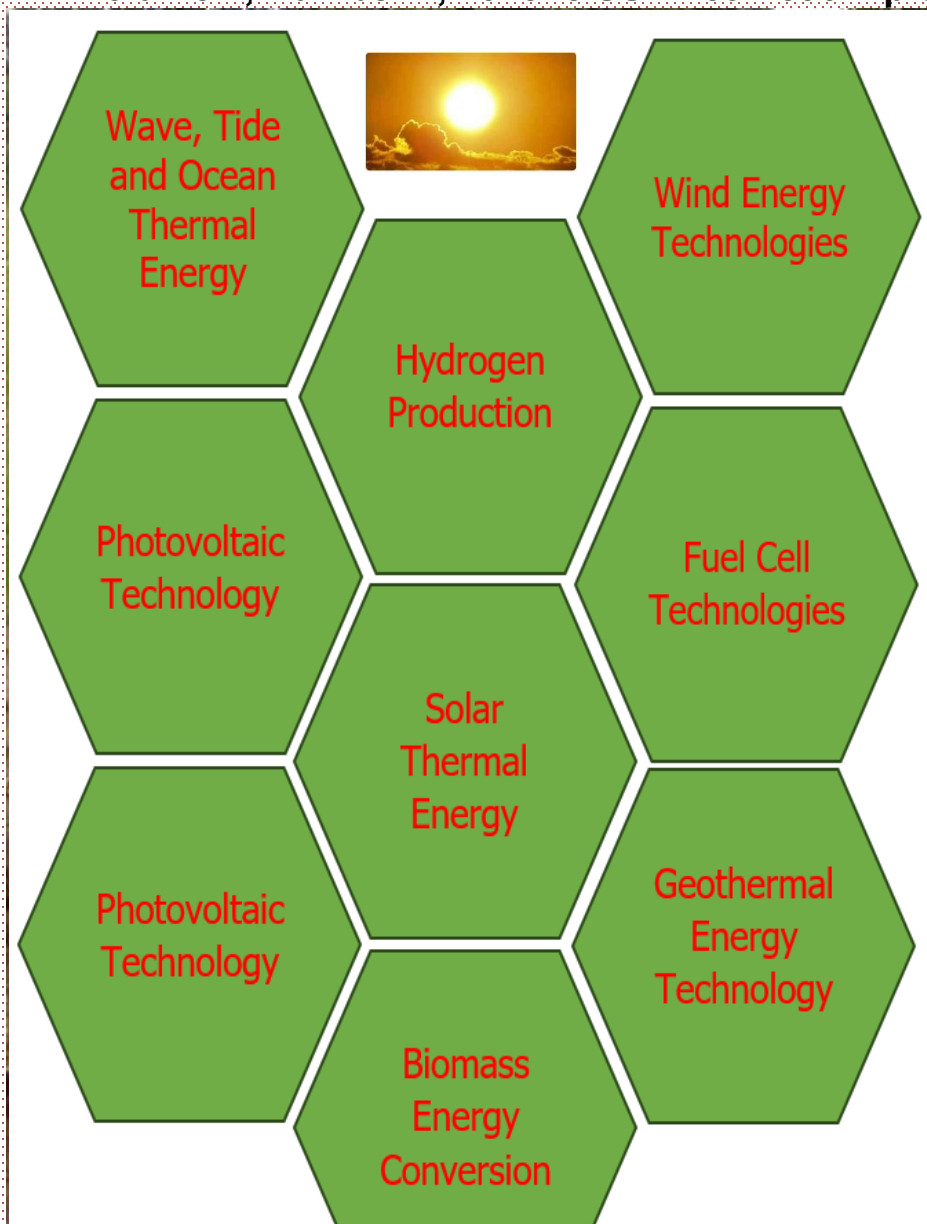
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