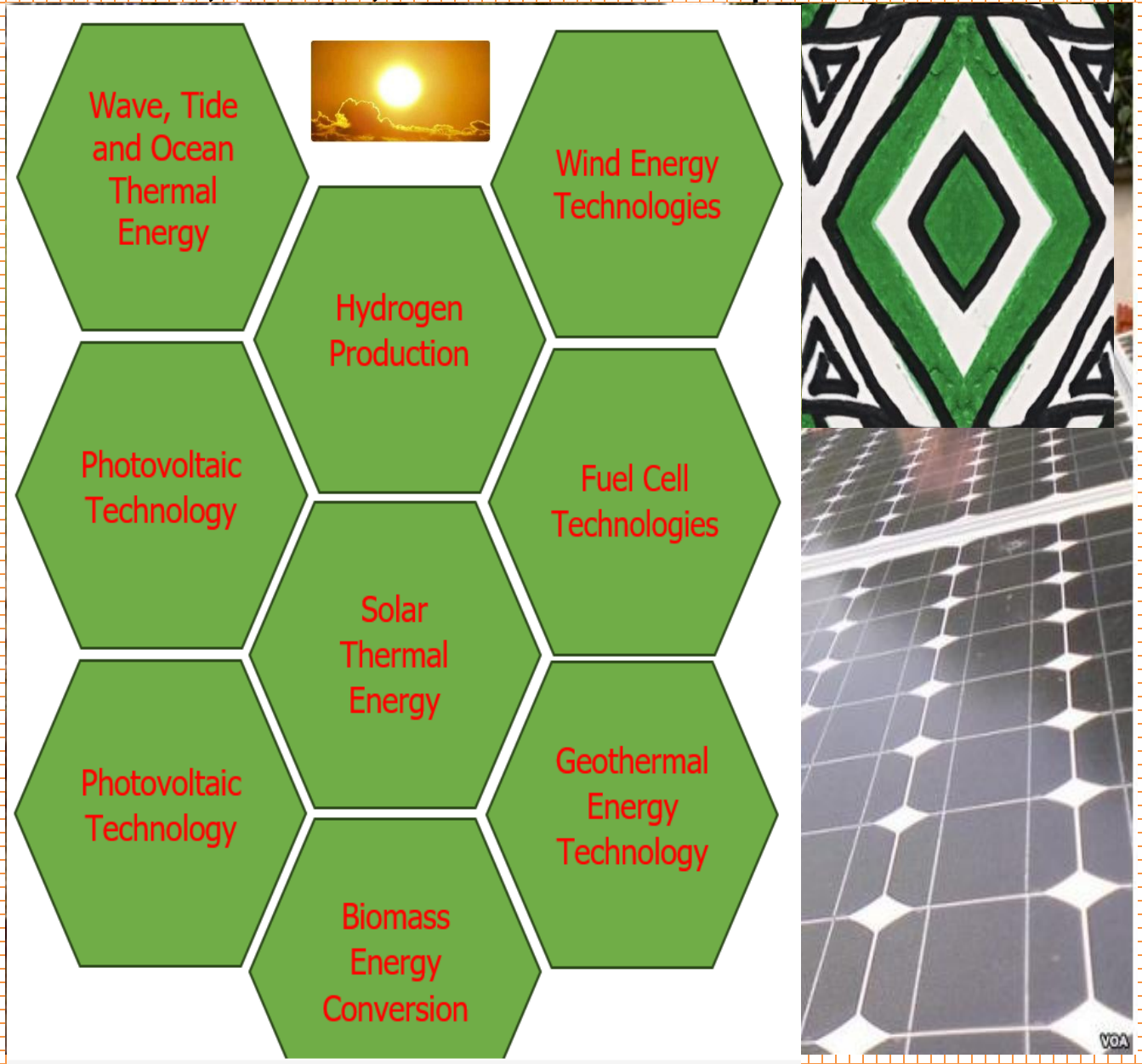




# Nigerian Journal of Renewable Energy Research

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## **SCOPE**

The **Nigerian Journal of Renewable Energy Research** delivers intricate papers to the research community, aimed at sparking additional studies or advancements. This publication is biannual. Within its pages, the Journal presents original articles, detailed reports, and critical reviews. Authors are urged to contribute manuscripts that address essential voids in the field of Renewable Energy research and evolution.

The Nigerian Journal of Renewable Energy Research is dedicated to advancing and sharing knowledge on the diverse topics and technologies related to renewable energy systems and components. Its objective is to assist professionals such as researchers, engineers, economists, manufacturers, NGOs, associations, and societies to stay updated with the latest advancements in their respective areas, ensuring the integration of sustainable energy alternatives into existing practices.

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Original research articles and review papers are accepted by the **Nigerian Journal of Renewable Energy Research**. However, review papers are by the Lead Editor's invitation only. Prospective authors for review papers are advised to submit an outline of their proposed paper along with a brief CV of the main author/s to the Editor-in-Chief for prior approval.

Contributions aligning with the United Nations' sustainable development goals, especially SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), are particularly welcomed.

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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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## THE PHYSICS AND APPLICATIONS OF SOLAR ENERGY: UNDERSTANDING SOLAR FUSION, RADIATION, TECHNOLOGIES AND MODERN UTILISATION

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#### Abstract

*The sun is the primary engine driving nearly all natural and technological energy systems on Earth. This article presents a comprehensive exploration of the scientific mechanisms by which the sun generates and delivers energy, beginning with nuclear fusion processes that convert hydrogen into helium via the proton–proton cycle. These reactions release immense quantities of thermal and electromagnetic radiation that sustain life and form the basis for renewable energy systems. The paper examines the structure and temperature profile of the sun, the historical evolution of theories about its energy source, and modern understanding of mass–energy conversion and binding energy. It further explains solar radiation behaviour, including atmospheric scattering, diffuse and direct components, and spatial–temporal variation in solar irradiance.*

*The study then transitions to contemporary solar technologies, detailing photovoltaic mechanisms, silicon doping, solar cell generations, concentrated photovoltaics, and solar thermal systems such as flat-plate collectors, evacuated tubes, parabolic troughs, and thermal energy storage techniques. Global renewable energy trends based on IEA projections are reviewed, highlighting solar PV as the fastest-growing energy technology and a major contributor to future electricity supply. Additionally, diverse applications of solar energy—including ventilation, water and space heating, pumping, lighting, cooking, and battery charging—are discussed alongside the environmental, economic, and operational challenges that limit its large-scale deployment. Despite issues of intermittency, land demand, manufacturing pollution, high initial costs, and low efficiency, solar energy remains one of the most promising long-term renewable resources. The article concludes that ongoing innovation in materials science, storage technologies, and system integration is essential for achieving cost-effective, efficient, and sustainable solar utilisation in the decades ahead.*

## **1. INTRODUCTION**

The sun serves as the fundamental energy source for Earth, driving climate systems, sustaining ecological processes, and enabling virtually all life forms through photosynthesis. As a massive nuclear fusion reactor composed primarily of hydrogen and helium, the sun continuously converts matter into energy through the proton–proton (pp) fusion cycle under extreme temperatures and pressures (Severino, 2017). This fusion process transforms approximately 508 million tonnes of hydrogen into 504 million tonnes of helium each second, releasing nearly four million tonnes of converted mass as radiant energy (Green et al., 2004). The abundance, reliability, and longevity of solar radiation—expected to continue for billions of years—position solar energy as a vital focus for renewable energy research and technological development (West, 1993).

Understanding the scientific mechanisms behind solar energy production is foundational for harnessing this resource efficiently. Early scientific explanations of solar energy relied on chemical combustion analogies, which proved inadequate after geological evidence showed Earth’s age exceeded 100 million years, far surpassing the lifespan chemical reactions could sustain (Bland, 2004). Subsequent hypotheses, such as gravitational contraction proposed by Helmholtz, extended estimates to millions of years but remained insufficient to explain the sun’s multi-billion-year lifecycle (Cahan, 2004). It was not until the early 20th century—following the discovery of nuclear reactions, atomic structure, and Einstein’s mass–energy equivalence—that scientists correctly attributed the sun’s energy source to nuclear fusion.

Modern solar technologies, including photovoltaic (PV) systems and solar thermal collectors, are rooted in these scientific principles. Solar PV cells convert sunlight into electricity using semiconductor materials such as silicon, while solar thermal systems capture solar heat for domestic, commercial, or industrial use (Tiwari, 2005). Advances in materials science have produced multiple generations of solar technologies, ranging from monocrystalline silicon panels to thin-film and concentrated photovoltaic (CPV) systems (Misak & Prokop, 2016). Meanwhile, global energy trends indicate unprecedented expansion in renewable energy capacity, particularly solar PV, which now represents the fastest-growing electricity source worldwide (International Energy Agency [IEA], 2024).

Despite its potential, solar energy faces challenges including intermittency, land requirements, manufacturing impacts, and high upfront system costs. Nonetheless, ongoing research on energy storage, solar fuels, semiconductor innovation, and system integration aims to increase efficiency and reduce environmental and economic barriers. This article examines the scientific foundations of solar energy, the mechanisms of solar radiation, the evolution of solar technologies, and the expanding global role of solar power in modern energy systems.

## **2. LITERATURE REVIEW**

The scientific understanding of solar energy begins with the nature of the sun as a fusion-based energy source. Nuclear fusion occurs when hydrogen nuclei combine to form helium under extreme temperature and pressure conditions in the solar core (Severino, 2017). The dominant energy pathway in sun-like stars is the proton–proton (pp) chain, which releases energy in the form of gamma radiation, neutrinos, and kinetic energy of reaction byproducts (Green et al., 2004). Einstein’s mass–energy relation ( $E = mc^2$ ) explains how the small mass difference between reactants and products is converted into enormous amounts of energy (Cahan, 2004). This discovery resolved earlier misconceptions attributing the sun’s heat to chemical or gravitational mechanisms (Bland, 2004).

Solar radiation reaching Earth consists of direct and diffuse components influenced by

atmospheric scattering, absorption, and reflection (Goga, 2010). The Earth's axial tilt, orbital geometry, and atmospheric composition cause spatial and temporal variations in solar irradiance (Newton, 2015). Measurements of radiation in watts per square meter ( $\text{W}/\text{m}^2$ ) or  $\text{kWh}/\text{m}^2$  are essential for solar energy system design, especially in the placement of photovoltaic and thermal collectors (U.S. Department of Energy, 2021). The distribution of solar radiation determines site suitability, system output, and technology selection.

Photovoltaic technology converts sunlight directly into electricity using semiconductor materials such as silicon, cadmium telluride, or copper indium gallium diselenide (CIGS). The foundational mechanism relies on the photoelectric effect, where absorbed photons excite electrons, creating an electric current (Tiwari, 2005). Silicon remains the dominant PV material due to its stability, abundance, and favourable electronic properties. Monocrystalline silicon panels achieve efficiencies above 20%, while polycrystalline panels typically reach around 15% efficiency (GreenMatch, 2015). Thin-film technologies, including amorphous silicon (a-Si) and CdTe, offer advantages in flexibility and lower production cost, though often at lower efficiencies.

Emerging PV innovations include concentrated photovoltaics (CPV), which use lenses or mirrors to focus sunlight onto high-efficiency multi-junction cells capable of exceeding 40% efficiency (Misak & Prokop, 2016). Biohybrid solar cells represent another research frontier, mimicking photosynthesis pathways to potentially achieve much higher conversion efficiencies (Tiwari, 2005).

Solar thermal systems capture solar heat for domestic, industrial, or power-generation purposes. Flat-plate collectors and evacuated tubes are widely used for water heating, while parabolic troughs, heliostats, and Fresnel lenses enable high-temperature applications such as electricity generation (O'Keefe & Pike, 2004). Energy storage technologies—including sensible heat storage, latent heat using phase change materials (PCM), and high-temperature molten salt systems—enhance system reliability by enabling thermal retention and dispatchability (Tiwari, 2005).

Chemical storage methods, such as thermochemical reactions using  $\text{Ca}(\text{OH})_2$ , offer long-duration storage potential but require further research to reduce operating temperatures and improve reversibility. According to the IEA (2024), solar PV is responsible for roughly 80% of projected renewable energy expansion through 2030, with global capacity expected to more than double. Falling costs, supportive policies, and improved manufacturing have made PV one of the most cost-effective electricity sources worldwide. China leads global deployment, while India, the EU, Middle East, and North Africa show rapid adoption trends. Challenges remain, including supply chain concentration, grid integration, financing barriers, and limitations in energy storage.

Despite its benefits, solar energy adoption faces several obstacles. Environmental concerns include land use impacts, toxic materials in PV manufacturing, and end-of-life waste disposal (Murphy-Mariscal et al., 2018). Economic challenges involve high upfront system costs, lengthy payback periods, and the continued expense of battery storage (Walden Labs, 2021). Intermittency and dependence on weather conditions further require robust storage and grid integration strategies. Nonetheless, continued technological innovations promise to improve performance, reduce costs, and enhance sustainability.

### **3. The energy of the sun. Comprehending the mechanisms of solar function**

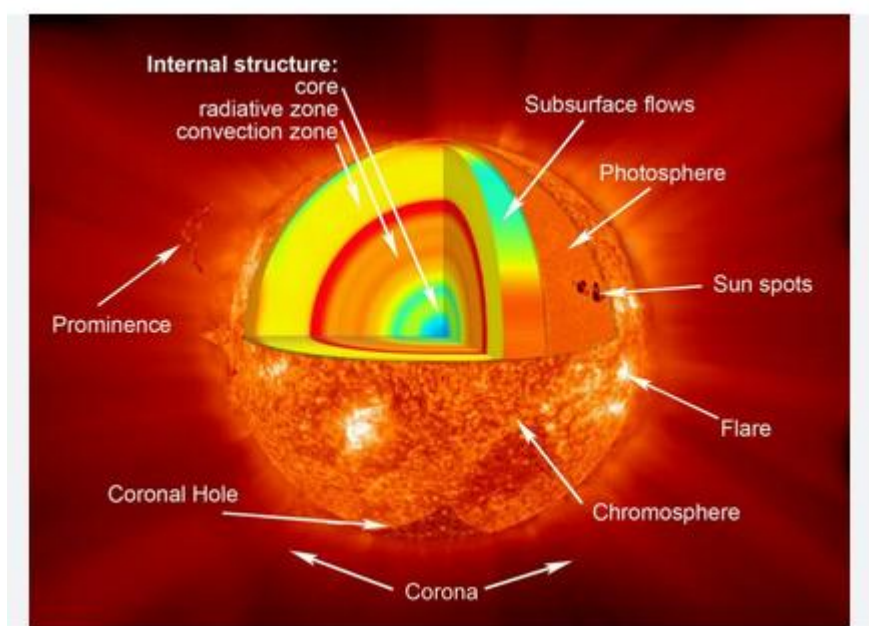
#### **3.1 Thermal energy and Light**

The sun (Figure1) is a colossal fusion reactor. Fusion refers to the process of combining hydrogen atoms to form helium. This transpires on the sun due to its extreme heat. The sun is exceedingly hot due to the substantial heat released by fusion processes. Fusion is referred to be a chain reaction for this reason. The energy source is derived from fusion events that convert hydrogen into helium, predominantly via the proton-proton (pp) cycle (Severino G., 2017).

The sun's nuclear fusion process transforms 508 million tonnes of hydrogen into 504 million tonnes of helium each second. The residual 4 million tonnes of matter are transformed into energy, resulting in an exceedingly high core temperature of the sun. Albert Einstein discovered that a little quantity of matter can be transformed into a substantial amount of energy. One ounce of matter transformed to energy by fusion might provide sufficient energy for a whole year for your home and vehicle, in addition to serving the needs of five thousand other households and vehicles.

Solar radiation is superior to alternative energy sources due to its abundance and longevity, expected to persist for millions of years (West M., 1993).

What is the origin of the sun's energy? This subject is vital, given solar light and heat underpin nearly all life on Earth. Sunlight sustains plant life through photosynthesis, whereas animals depend on consuming plants for survival. Nearly all microscopic life forms (bacteria, protozoa, etc.) sustain themselves by harnessing solar energy.



**Figure. 1** Composition of the Sun

Source: <https://science.nasa.gov/blogs/the-sun-spot/2023/09/26/layers-of-the-sun/>

#### **3.2 Surface Temperature**

The sun is a spherical body with a diameter of 1,400,000 km, composed primarily of heated gases, predominantly hydrogen and helium, with a surface temperature of approximately 6,000 degrees Celsius (around 11,000 degrees Fahrenheit). Any surface at that temperature will emit heat and light. The burners of an electric stove or toaster oven do not reach 6,000 °C; yet, when activated, they become "red hot," emitting both heat and red light. If we could elevate the

temperature to 6,000 °C. They would attain a "white hot" state and radiate light akin to that of the sun. A fire is a zone of gases with a temperature sufficiently elevated to produce heat and light (Goga, 2010). The inquiry shifts from the origins of heat and light to the source of energy that maintains the sun's surface temperature at 6,000 degrees.

For a scientist in the 18th or 19th century, before to the advent of electrical gadgets, the most probable method of comprehending the sun's energy would be to draw a parallel to fire. A combustion occurs when a material reacts chemically with oxygen in the air. Despite the lack of knowledge regarding the sun's chemical composition, one could reasonably infer that a chemical reaction occurs, generating heat and maintaining the sun's temperature. The issue is determining the duration until the combustible chemicals are entirely consumed and the fire extinguishes, analogous to how logs in a fireplace reduce to ash within a few hours.

### **3.3 The lifespan of the sun**

Arriving at a preliminary answer to that issue is straightforward, as we possess knowledge of the sun's mass. The mass is determined through the law of universal gravity and the established orbits of the planets. Assuming the mass consists entirely of carbon, one can estimate the sun's lifespan to be approximately 50,000 years. Any chemical combustion will result in a lifespan within the approximate range (Bland P., 2004).

Nineteenth-century geologists posited that the Earth's age exceeded 100 million years. The calculations were estimative, grounded in plausible assumptions regarding the deposition of salt into the ocean and the accumulation of marine sediment onto the present continents. Assuming that all oceanic salt originated from river deposition, and given the current deposition rate, we can calculate the duration required to achieve the present salt concentrations in the oceans. Furthermore, since the Earth orbits the Sun, it is difficult to conceive of the Earth being older than the Sun. Consequently, the concept of the sun as a chemical fire was untenable.

### **3.4 Gravitational Energy**

In approximately 1850, physicist Hermann von Helmholtz posited that the sun's energy source may be attributed to gravitation, specifically the universal gravitational force exerted by each component of the sun on every other component (Cahan D., 2004). Gravity may generate energy, as illustrated by the act of dropping an object, such as a baseball, and allowing it to descend to the earth. Kinetic energy is generated when the ball descends. Considering the sun as a vast sphere of gases, each atom within the gas experiences a net gravitational pull towards the centre of the sphere, resulting in a collective inclination of all atoms to "descend" towards the core. During this process, they hit with other atoms, resulting in intense yet random motion. The fast, erratic movement of atoms in a gas indicates elevated temperatures. Based on the established energy production rate of the sun, Helmholtz was able to approximate the duration for which the sun, considering its mass, could sustain this energy generation. His findings indicated a duration of approximately 20 million years, far above the estimate derived from chemical combustion, and aligning more closely with contemporary assessments of the Earth's age.

Billions of years; nonetheless, millions of years are insufficient. The most accurate estimate for the age of the solar system, including the sun and the planets, is 4.6 billion years. Radioactive dating indicates that certain rocks solidified approximately 4 billion years ago, and that primitive bacteria emerged nearly 3.5 billion years ago. Thus, gravitation cannot account for the source of the sun's energy.

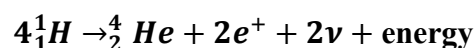
### **3.5 Nuclear Reactions**

The convergence of significant developments occurred in the early twentieth century with the

identification of the atomic nucleus (1911), the investigation of nuclear reactions (1920s), and Einstein's theory of relativity (1905). In a standard nuclear reaction, many subatomic particles converge, interact, and yield various (potentially distinct) particles. A series of reactions occur in the sun, culminating in the following combination of particles.

### **3.6 Hydrogen combustion**

The overall nuclear fusion reaction in the Sun, where four hydrogen nuclei fuse into one helium nucleus, is:



This process is more accurately a series of reactions, known as the proton-proton chain, where hydrogen protons combine under extreme heat and pressure to form helium, releasing energy in the form of positrons ( $e^+$ ), neutrinos ( $\nu$ ), and photons ( $\gamma$ ). The left side of this reaction displays four protons and four electrons, essentially representing four hydrogen atoms. Hydrogen serves as the fundamental beginning point, as the majority of matter in the sun and other stars consists of hydrogen gas. Hydrogen, being the most fundamental element, logically suggests that a significant portion of the cosmos in its primordial state would consist of hydrogen. The terminus is helium, recognised as the second most prevalent element in the sun. The process is commonly termed "hydrogen burning" to helium, with hydrogen frequently designated as "fuel"; nevertheless, it is essential to recognise that this reaction does not constitute burning in the conventional sense of a chemical reaction involving a fuel, such as coal or wood, and oxygen. This constitutes a nuclear reaction (Green et al., 2004).

### **3.6 Mass Transformed into Energy**

Energy is produced during this reaction due to the total mass of the particles on the right side being smaller than that on the left side. The deficiency of electrons on the right is not the sole factor. The primary distinction is that the mass of the helium nucleus ( ${}^4_2\text{He}$ ) is significantly lower than the cumulative mass of the four protons on the left. This exemplifies binding energy: The isotope  ${}^4_2\text{He}$  comprises two protons and two neutrons, although its mass is inferior to the cumulative mass of the individual protons and neutrons. Given that the mass on the left side exceeds that on the right, energy is generated throughout the reaction, equivalent to the mass difference multiplied by  $c^2$ . This energy exists in two forms: the kinetic energy of particles in the sun and gamma radiation.

### **3.7 The Proton-Proton Cycle**

Equation (1) represents the cumulative result of a sequence of more fundamental reactions. The procedure outlined in Equation (1) is referred to as the proton-proton cycle, as it commences with the contact of two protons. The process of combining tiny nuclei to form larger ones is termed fusion, and the sequence occurring in the sun resembles (though is not identical to) the fusion reactions being investigated as a potential source of electrical energy on Earth (Severino G., 2017).

### **3.8 The binding energy of the alpha particle**

What is the reason behind nature (the sun and the stars) exerting such effort to create  ${}^4_2\text{He}$ 's? Among the several tiny nuclei participating in the proton-proton cycle,  ${}^4_2\text{He}$  is the most tightly bonded. The binding energy of  ${}^4_2\text{He}$  is significantly substantial, indicating that its formation by nature results in the release of a considerable quantity of energy. Energy is released at each stage of the cycle, with the majority occurring in the last step, where  ${}^4_2\text{He}$  is produced.

### **3.9 Gravitational Collapse**

The prevailing concept for the sun's beginning posits that a cloud of hydrogen gas initiates collapse due to its own gravitational forces, leading to an increase in temperature. While this cannot serve as the mechanism for the sun's energy generation over billions of years, it may function as a triggering or ignition mechanism (O'Keefe and Pike, 2004).

### **3.10 A heated plasma**

Consequently, the cloud compresses, and at elevated temperatures, the gas transforms into a plasma. The hydrogen atoms dissociate into protons and electrons, which then exhibit random motion. The temperature reaches its peak near the centre of the cloud, where protons exhibit such high energy that the reaction in Equation (1) commences, initiating the proton-proton cycle.

### **3.11 Equilibrium**

These activities persist at the core of the cloud, elevating the temperature to approximately 10,000,000 degrees. At this temperature, the sun attains equilibrium, when the outward pressure from the "combusting" gases counterbalances the gravitational force exerting an inward draw on the matter. The energy generated in the core consistently radiates outward, maintaining the sun's overall temperature. The outside areas are significantly cooler than the centre; nonetheless, they possess sufficient heat to emit energy into space, manifested as the heat and light that illuminate the Earth (Green and Jones, 2004).

### **3.12 The lifespan of the sun**

The sun can maintain this equilibrium for around 10 billion years. Considering the sun's age is approximately 4.6 billion years, it may be inferred that we have roughly 5 billion years remaining. Ultimately, the majority of the hydrogen in the core will be depleted, leading the sun into a terminal phase. The proton-proton cycle fuels not just the sun but also the majority of medium to small mass stars. Stars exceeding the size of the sun generate energy through a more intricate series of processes; yet, the overall outcome remains consistent with Equation (1), wherein hydrogen is converted into helium (Tyson, 2017).

### **3.13 Solar Radiation**

Commonly referred to as solar resource, it denotes the electromagnetic radiation emitted by the sun. Solar radiation can be harnessed and converted into valuable energy forms, including heat and electricity, through various technologies. The technical feasibility and economic viability of these systems at a particular site are contingent upon the solar resource availability. Every area on Earth receives sunlight for a portion of the year. The quantity of solar radiation that reaches a specific location on the Earth's surface fluctuates according on:

- a. Geographical place
- b. Temporal designation
- c. Period
- d. Regional topography

## **4. REGIONAL METEOROLOGICAL CONDITIONS**

The Earth's spherical shape causes sunlight to touch the surface at varying angles, from 0° (horizon level) to 90° (straight overhead). When the sun's beams are perpendicular, the Earth's surface receives maximum energy. The greater the angle of the sun's rays, the longer their passage through the atmosphere, resulting in more scattering and diffusion. The Earth's spherical shape results in the polar regions never experiencing direct sunlight, and due to the axial tilt, these locations receive no sunlight at all for a portion of the year. The Earth orbits the sun in an elliptical path, being nearer to the sun at certain times of the year. When the sun is closer to the Earth, the Earth's surface receives additional solar energy. The Earth is closer to the sun during summer in

the southern hemisphere and winter in the northern hemisphere. Nonetheless, the existence of extensive oceans mitigates the anticipated hotter summers and colder winters in the southern hemisphere due to this disparity.

The 23.5° inclination of the Earth's rotational axis is a crucial determinant of the solar irradiance received at specific locations on the planet. Axial tilt causes extended daylight in the northern hemisphere from the vernal equinox to the autumnal equinox, whereas the southern hemisphere experiences prolonged daylight for the subsequent six months. The equinoxes, occurring annually on or around March 23 and September 22, have days and nights that are precisely 12 hours in duration.

The sun is the source of all energy on Earth. Plants utilise sunlight to synthesise nourishment. Decomposed vegetation from hundreds of millions of years ago generated the coal, oil, and natural gas utilised today. Solar energy is mostly harnessed through the utilisation of solar cells. Solar energy can indeed be utilised to illuminate or heat a room through strategically positioned windows and skylights. Solar energy can also be utilised to dry our garments in sunlight. Solar cells are utilised to harness solar energy for powering electrical gadgets.

<https://www.energy.gov/eere/solar/articles/solar-radiation-basics>

#### **4.1 Fundamental Principles of Solar Energy**

Solar energy is generated by the light and heat emitted by the sun, manifesting as electromagnetic radiation. Contemporary technology enables us to harness this radiation and convert it into practical forms of solar energy, like heating and power. Solar energy is the continuous energy produced by the sun's nuclear fusion reactions. The average solar radiation intensity at Earth's orbit is 1367 kW/m<sup>2</sup>. The Earth's equatorial circumference is 40,000 km, allowing for the calculation of energy received by the Earth, which is around 173,000 TW. At sea level, the standard peak intensity is 1 kW/m<sup>2</sup>, while a place on the Earth's surface receives an annual average radiation intensity of 0.20 kW/m<sup>2</sup>, equating to approximately 102,000 TW of energy over 24 hours. Humans depend on solar energy for survival, alongside all other renewable energy sources, excluding geothermal resources. Although the total solar energy available is ten thousand times greater than human energy consumption, its low density and variability due to location and season present significant challenges for the development and utilisation of solar energy (Tiwari G, 2005).

The need for this sector of renewable energy sources is increasingly rising due to global economic development and population growth. The latest IEA research indicates that, driven by solar energy, renewables are projected to satisfy about half of worldwide electricity consumption by the decade's conclusion.

According to a new IEA report released today, supportive policies and favourable economic conditions are anticipated to drive a significant increase in the world's renewable power capacity throughout the remainder of this decade, with global additions projected to approximate the current power capacity of China, the European Union, India, and the United States combined.

The Renewables 2024 report, the IEA's premier yearly publication on the industry, indicates that the global addition of renewable energy capacity would exceed 5,500 gigawatts (GW) from 2024 to 2030, nearly tripling the increase observed from 2017 to 2023.

The analysis indicates that China is projected to represent over 60% of the total renewable capacity installed globally from now until 2030, contingent upon prevailing market trends and current governmental policy frameworks. By the end of this decade, China is projected to account

for about fifty percent of the global renewable power capacity, an increase from one-third in 2010. China is increasing its renewable energy capacity the most, while India is expanding at the highest rate among major economies.

Solar photovoltaic technology is projected to constitute a substantial 80% of the expansion in worldwide renewable capacity from now until 2030, driven by the establishment of new large-scale solar power facilities and a rise in rooftop solar installations by businesses and residences. Despite persistent hurdles, the wind sector is positioned for a resurgence, with the growth rate expected to double from 2024 to 2030 compared to the interval from 2017 to 2023. Currently, wind and solar photovoltaic technologies represent the most economical choices for augmenting electricity generation in nearly all nations.

Consequently, about 70 nations, which together represent 80% of worldwide renewable power generation, are set to achieve or exceed their existing renewable targets for 2030. The expansion does not entirely align with the objective established by almost 200 governments at the COP28 climate change summit in December 2023 to triple the world's renewable capacity within this decade; the analysis predicts that global capacity will attain 2.7 times its 2022 level by 2030. However, IEA analysis suggests that achieving the triple aim is completely feasible if governments capitalise on immediate possibilities for action. This entails delineating ambitious strategies in the forthcoming iteration of Nationally Determined Contributions under the Paris Agreement, scheduled for next year, and enhancing international collaboration to reduce elevated financing costs in emerging and developing economies, which are hindering the expansion of renewable energy in high-potential areas like Africa and Southeast Asia.

Renewable energy sources are advancing more rapidly than national governments can establish targets for them. According to IEA Executive Director Fatih Birol, this trend is primarily motivated not only by the desire to reduce emissions or enhance energy security, but increasingly because renewable energy sources now represent the most cost-effective solution for establishing new power plants in nearly all nations globally. This analysis indicates that the expansion of renewable energy, particularly solar power, will revolutionise electricity networks worldwide within this decade. By 2030, the global renewable power capacity is projected to increase by about 5,500 gigawatts, approximately equivalent to the current power capacity of China, the European Union, India, and the United States combined. By 2030, we anticipate that renewable energy sources will fulfil fifty percent of worldwide electricity consumption.

By the conclusion of this decade, the proportion of wind and solar photovoltaic energy in worldwide electricity generation is projected to quadruple to 30%, as per the forecast. The analysis underscores the necessity for governments to intensify their efforts to securely incorporate these variable renewable sources into power infrastructure. Recently, the incidence of curtailment—where renewable electricity generation is not utilized—has significantly risen, currently approximating 10% in various nations. Countries should prioritise enhancing power system flexibility to address this issue. A concerted effort to resolve policy ambiguities and expedite permitting procedures, alongside the construction and modernisation of 25 million kilometres of electricity grids and achieving 1,500 GW of storage capacity by 2030, as emphasised in prior IEA analyses, would facilitate a greater proportion of electricity generation from renewable sources.

The proportion of renewables in final energy consumption is projected to rise to about 20% by 2030, up from 13% in 2023, mostly driven by the substantial expansion of renewable power. Concurrently, renewable fuels, addressed in a dedicated chapter of the report, are underperforming, highlighting the necessity for targeted policy assistance to decarbonise sectors

that are challenging to electrify. The analysis indicates that achieving international climate objectives necessitates not only the expedited deployment of renewable energy but also a substantial acceleration in the uptake of sustainable biofuels, biogases, hydrogen, and e-fuels. Due to their higher costs compared to fossil fuels, their proportion in global energy is projected to stay under 6% by 2030.

The research additionally examines the condition of manufacturing in renewable technologies. Global solar production capacity is anticipated to exceed 1,100 GW by the conclusion of 2024, more than doubling the projected demand. The supply surplus, primarily in China, has contributed to a reduction in module costs, which have decreased by almost fifty percent since early 2023; nevertheless, this situation has also resulted in substantial financial losses for some manufacturers.

In light of the increasing worldwide emphasis on industrial competitiveness, solar PV production capacity in both India and the United States is projected to triple by 2030, contributing to global diversification. Producing solar panels in the United States is three times more costly than in China and twice as expensive as in India. The research advises authorities to balance the higher costs and benefits of local production, prioritising job growth and energy security.

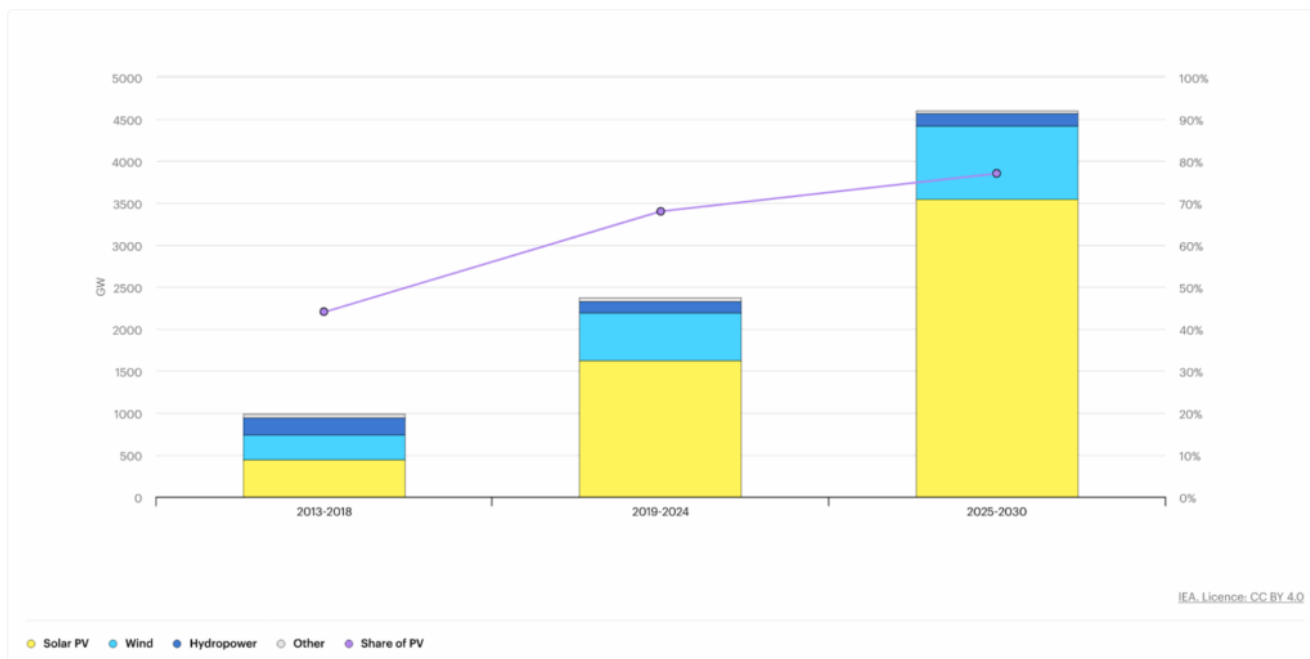
#### **4.2 Renewable Energy Trends 2025: Capacity to Double by 2030**

Notwithstanding the favourable trends, the IEA cautions that the COP28 goal of tripling clean energy capacity is unattainable. To regain momentum, nations should mitigate regulatory ambiguities, shorten permitting durations, enhance grid investments, broaden flexibility to support the integration of intermittent renewables, and alleviate finance risks. In early October 2025, the IEA published its “Renewables 2025” report, an annual sectoral analysis that outlines the current trends, projections, challenges, and opportunities in renewable energy, informed by recent legislation and market developments. The analysis indicated that, despite challenges, renewable energy, particularly solar PV, continues to expand globally—a crucial trend for maintaining the Paris Agreement objectives. Significantly, the persistent reduction in technology and energy prices, together with the advantages of energy security, will markedly expedite the deployment of renewable energy capacity in several nations, with Asia poised to emerge as the most dynamic market. The IEA's Renewables 2025 report indicates that global renewable energy trends forecast an addition of 4,600 GW in new capacity by 2030.

The primary conclusion of the IEA's analysis is that worldwide renewable power capacity is projected to double by 2030, increasing by 4,600 GW. The organisation observes that this is about tantamount to incorporating the power generation capacity of China, the EU, and Japan collectively into the global energy mix. The agency anticipates that renewables will emerge as the predominant global energy source, accounting for over 45% of power generation by 2030, with an increase of 60% — from 9,900 TWh in 2024 to 16,200 TWh in 2030.

#### **4.3 Solar Energy**

The IEA reports that solar PV, projected to more than quadruple in the next five years, constitutes about 80% of the global rise, succeeded by wind, hydropower, biofuels, and geothermal energy. The government observes that reduced costs, expedited permitting, and widespread social acceptability will facilitate growth. The increase in retail electricity rates due to the energy crisis has spurred the adoption of solar photovoltaic systems, prompting individuals and companies to install these systems to lower their electricity expenses.



**Figure 2.** Renewable Electricity Capacity Growth by Technology Segment, and Solar PV Share, Main Case, 2013-2030. Source:([IEA](#))

#### 4.4 Wind Energy

The organisation indicates that worldwide wind power capacity is projected to roughly double to exceed 2,000 GW by 2030, primarily propelled by China and the EU. Relative to the prior era (2019-2024), the IEA's projection anticipates a 45% increase in cumulative onshore wind capacity additions from 2025 to 2030, totalling 732 GW. Offshore wind capacity expansion is projected to exceed 140 GW, more than twice the growth of the preceding five-year period. The yearly offshore wind market grows from 9.2 GW in 2024 to over 37 GW by 2030, with China representing nearly 50% of this growth.

#### 4.5 Hydroelectric power

The IEA forecasts that hydropower will constitute 3% of new renewable energy installations by 2030.

#### 4.6 Geothermal Energy

By 2030, annual geothermal capacity additions will achieve a record high, tripling the amount observed in 2024, propelled by advancements in the United States, Indonesia, Japan, Turkey, Kenya, and the Philippines.

The IEA acknowledges that, although the findings are promising, its prediction for the period from 2025 to 2030 is 5% lower than its study from 2024, indicating alterations in policy, regulation, and market conditions. The agency now anticipates a reduction of 248 GW in renewable capacity to be operational during the next five years. Solar and wind energy can fulfil energy requirements. Nonetheless, as per Ember's "Global Electricity Mid-Year Insights 2025" study, the contributions from solar and wind energy are already sufficient to satisfy the increasing worldwide electricity demand. Analysts report that solar and wind energy fulfilled all electricity demand growth in the first half of this year, resulting in a minor decline in fossil fuel generation relative to the same period in 2024. Significantly, Ember observes that renewable energy sources have surpassed coal for the first time in history, with unprecedented solar development and consistent wind expansion gradually transforming the global energy landscape. Solar and wind energy are expanding rapidly to satisfy the increasing global demand for electricity, stated

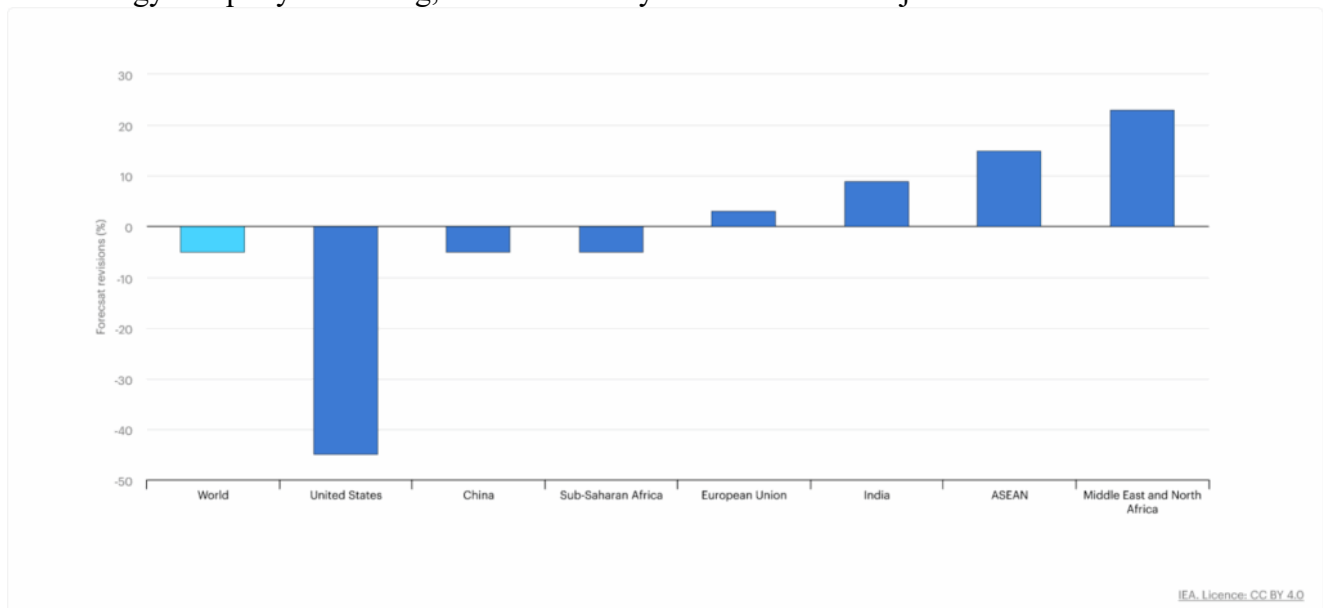
Małgorzata Wiatros-Motyka, senior electricity analyst at Ember. This signifies the onset of a transition in which clean energy is aligning with the growth in demand.

### **5. FOCUS ON IEA'S REGIONAL INSIGHTS AND TRENDS IN THE RENEWABLE ENERGY MARKET**

The IEA's analysis indicates that in over 80% of nations globally, renewable electricity capacity is projected to expand more rapidly from 2025 to 2030 than over the preceding five years. The organisation indicates that alterations in policy within the US and China account for the 5% reduction in the prediction for worldwide renewable power capacity increase compared to last year's study. The United States, under President Trump, is the primary outlier, with its projection adjusted downward by over 50%. Notwithstanding the transition from fixed tariffs to auctions and its effect on project economics, China still represents about 60% of worldwide renewable capacity expansion and is poised to achieve its recently declared 2035 wind and solar objective five years in advance.

The IEA's 2025 renewable market outlook is more favourable for India, Europe, and most emerging and developing markets compared to the prior edition. In India, the rise of renewable energy is propelled by increased auction volumes, enhanced support for rooftop solar initiatives, and expedited hydropower permitting processes. The IEA observes that the country is poised to achieve its 2030 objective and emerge as the second-largest growth market for renewables, with capacity projected to expand by 2.5 times within the next five years.

The IEA has adjusted its growth prediction for the EU somewhat upward, propelled by unexpectedly large installations of utility-scale solar PV capacity and robust corporate power purchase agreement (PPA) activity in significant countries. The expansion is adequate to counterbalance a diminished forecast for offshore wind, the experts observe. The Middle East and North Africa (MENA) area continues to excel, with its prediction increased by 25%. This represents the most substantial regional enhancement, propelled by the swift expansion of solar photovoltaic technology in Saudi Arabia. ASEAN ranks second behind the MENA area, exhibiting a 15% higher projection. In Southeast Asia, the deployment of solar photovoltaic and wind energy is rapidly advancing, characterised by more ambitious objectives and new auctions.



**Figure 3.** Renewable Capacity Expansion Changes from Renewables 2024 to Renewables 2025 in Selected Countries or Regions, 2025-2030. Source: [IEA](#)

The IEA's analysis indicates that the adoption of distributed solar PV systems with storage is increasing in nations with unreliable electrical grids, such as Pakistan, where the implementation of commercial and large-scale off-grid solar PV systems is significantly enhancing electricity availability. Annual onshore wind capacity additions throughout the forecast period are anticipated to increase across Africa, the Middle East, ASEAN nations, Latin America, and Eurasia, as well as in Europe and India.

This advancement is already occurring in China and India. Ember observes that both nations experienced a decline in fossil fuel generation during the first half of 2025, as the expansion of sustainable energy surpassed demand. China continued to dominate clean energy expansion, contributing more solar and wind capacity than the entirety of the global total, resulting in a 2% reduction in fossil fuel generation (58.7 TWh) during the first half of 2025.

During the same era in India, the expansion of clean energy sources exceeded the growth in demand by more than threefold. Nonetheless, demand remained remarkably low at 1.3% (12 TWh), in contrast to the corresponding period last year at 9% (75 TWh). India's unprecedented increase of solar and wind energy, along with diminished demand, resulted in a reduction of fossil fuel use, with coal decreasing by 3.1% (22 TWh) and gas by 34% (7.1 TWh).  
**Transition to Renewable Energy and Associated Challenges**

The IEA's research delineates several hurdles currently jeopardising the expansion of the renewable energy market, including overcapacity, depressed prices, trade impediments, and regulatory changes. These factors have hindered new investments in solar PV supply chains within China, whereas manufacturing capacity beyond China is currently increasing. The IEA cautions that obstacles, including grid integration, supply chain vulnerabilities, and financing, will escalate over the next five years.

The analysis forecasts that solar photovoltaic supply chains and rare earth elements for wind turbines will remain significantly concentrated in one country, underscoring supply chain security vulnerabilities. By 2030, supply chain concentration for critical production segments will persist over 90%, mirroring current levels, with China maintaining its dominance in the mining and processing of rare earth elements. Notwithstanding diversification initiatives, mining and refining are projected to remain significantly concentrated until 2030.

The agency observes that wind power would have supply chain difficulties, escalating costs, and permitting delays, with certain locations potentially unable to effectively tackle these constraints to facilitate expansion. The offshore wind sector is anticipated to encounter numerous hurdles in the forthcoming five years, with its projected growth adjusted downward by more than 25%. The IEA reports that numerous developers have already diminished their 2030 deployment objectives. The agency observes that diminished expectations are attributable to the policy shift in the United States and to project cancellations and delays in Europe, Japan, and India, resulting from elevated costs and supply chain difficulties.

The IEA observes that the rising proportions of wind and solar photovoltaic energy are exacerbating integration issues. By 2030, variable renewables are projected to account for approximately 30% of the global electricity supply, roughly double the current level. The agency indicates that this necessitates a swift enhancement of power system flexibility and grid investment across a growing number of nations.

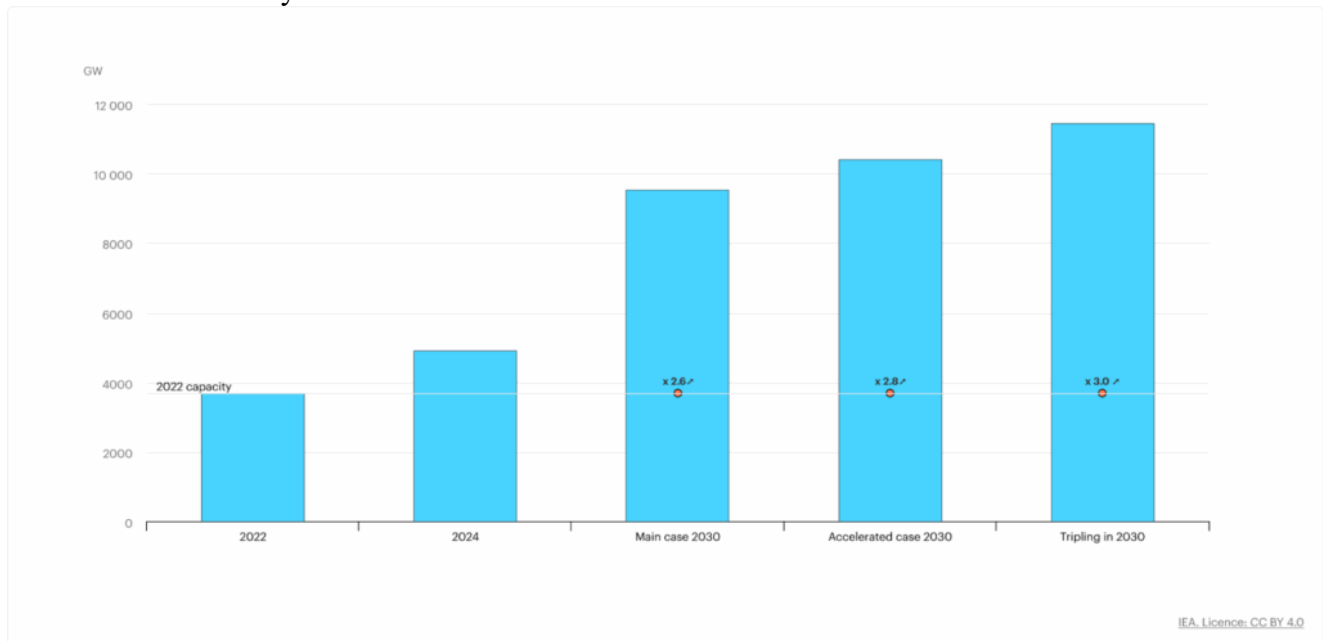
The IEA cautions that wind and solar producers face challenges, as many are already

experiencing financial difficulties and reporting substantial losses despite a rise in global installations. The agency indicates that the economic viability of equipment makers is a concern, referencing China, where solar PV prices have plummeted by more than 60% since 2023 due to an oversupply of modules and fierce rivalry for market share. This has reduced the margins of the top manufacturers to negative 10%, with total losses approaching USD 5 billion since the start of 2024. The agency reports that wind manufacturers outside of China have faced difficulties, with total losses amounting to USD 1.2 billion in 2024.

The IEA observes that the demand for clean energy from developers and purchasers continues to be robust over the forecasted period. Experts have determined that renewable developers have either augmented or sustained their capacity deployment objectives for 2030 since the previous year, with both developers and purchasers reaping advantages from reduced solar PV costs. Closing the Divide Between Aspiration and Execution is Essential for Tripling Clean Energy Capacity

The IEA projects that worldwide renewable power capacity will attain 2.6 times its 2022 level by 2030, although it will still be insufficient to meet the COP28 doubling commitment. Nevertheless, the agency observes that the objective remains attainable provided nations enact improved policies to address disparities in both aspiration and execution.

The IEA proposes an expedited scenario in which global renewable capacity might attain 2.8 times its 2022 level by 2030.



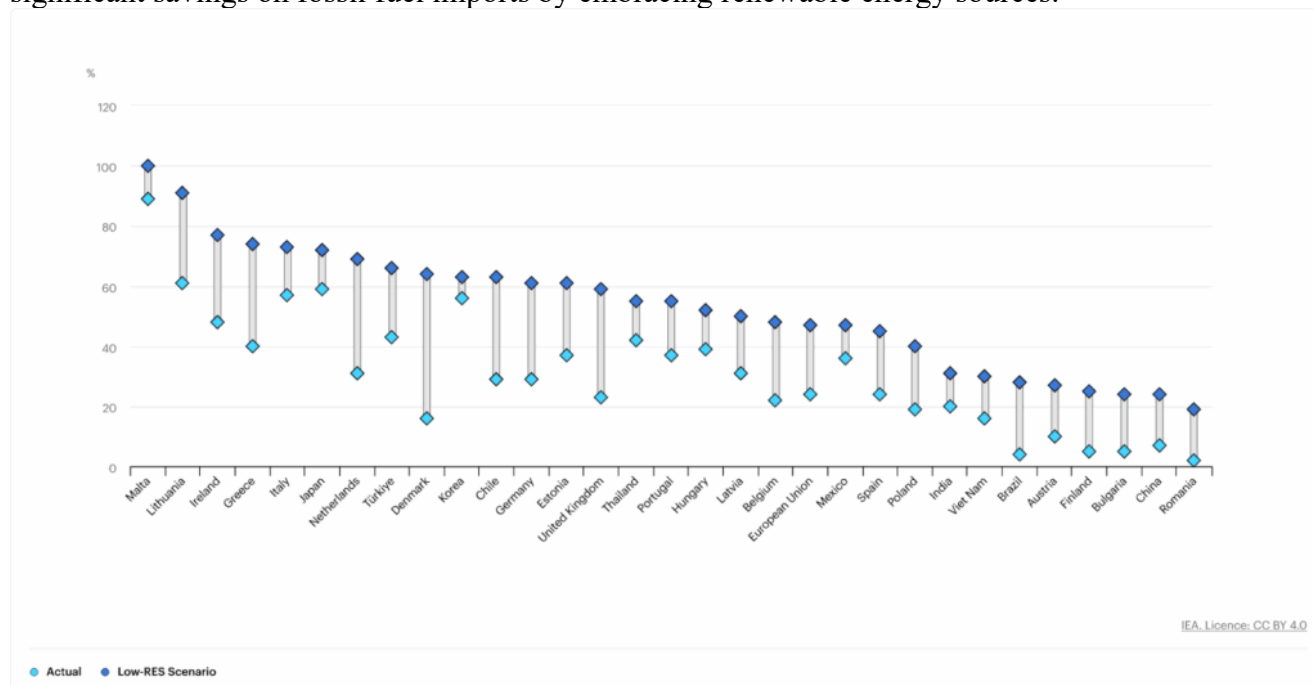
**Figure 4.** Renewable Capacity Growth and the Gap to Global Tripling, 2022-2030. Source: [\(IEA\)](#)

To facilitate this expansion, nations must mitigate regulatory uncertainty, shorten permission times, and enhance investment in grid infrastructure. Additional essential measures encompass enhancing flexibility to enable the incorporation of fluctuating renewables and mitigating financial risks.

This will assist nations in expediting their energy transition, yielding substantial economic, societal, and environmental benefits in the process. The IEA indicates that the implementation of renewable energy sources has substantially diminished fuel import requirements in numerous nations, hence improving energy diversification and security. The agency reports that, of the

2,500 GW of non-hydro renewable power capacity added worldwide since 2010, over 80% was implemented in nations dependent on fossil fuel imports. In the absence of these renewable contributions, total worldwide imports of coal and natural gas in these nations would have increased by 45% in 2023.

Consequently, nations have diminished coal imports by 700 million tonnes and natural gas imports by 400 billion cubic meters, resulting in an anticipated savings of USD 1.3 trillion since 2010. Countries such as Japan, South Korea, Thailand, India, and Vietnam have realised significant savings on fossil fuel imports by embracing renewable energy sources.



**Figure 5.** Fossil Fuel Import Dependence of Electricity Supply, Actual and in Low-RES Scenario, 2023. Source: (IEA)

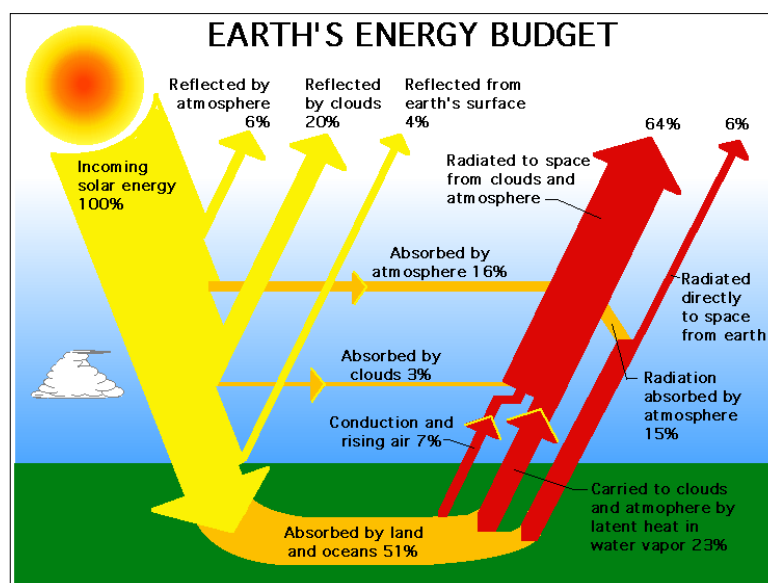
To secure the gains made thus far, Sonia Dunlop, CEO of Global Solar Council, emphasises the necessity for governments and business to expedite investments in solar, wind, and battery storage technologies. The expert asserts that this will guarantee the provision of clean, affordable, and reliable electricity to communities universally.

We are observing the initial indications of a significant turning point,” stated Ember’s Wiatros-Motyka. “With the declining costs of technologies, this is an opportune time to adopt the economic, social, and health advantages associated with enhanced solar, wind, and battery usage.

### 5.1 Accessible Solar Resource

It is improbable that there was ever a period when mankind failed to comprehend and value the Sun's contribution to the survival of the human race. (Newton, 2015). The technical feasibility and economic viability of utilising solar energy are contingent upon the quantity of accessible sunlight (solar radiation) in the designated location for solar heaters or panels. This is occasionally termed the accessible solar resource.

Every region on Earth receives sunshine at least once annually. “Part of the year” denotes the period during which the northern and southern polar caps experience complete darkness for several months annually. The availability of sunshine is a crucial issue to consider when evaluating the use of solar energy.



**Figure 6.** Earth s energy budget  
(source, <https://marine.rutgers.edu/cool/education/class/yuri/erb.html>)

Several more aspects must be considered when assessing the feasibility of solar energy in a certain region. The following are:

- Day and night result from the Earth's rotation, while seasons are attributed to the tilt of the Earth's rotational axis and its orbit around the sun, which is at an angle of  $23^{\circ}27'$ .
- The Earth rotates around its axis, which extends through its north and south poles, completing a round from west to east each day. The Earth's rotation causes day and night, with a rotation of 15 degrees each hour. Furthermore, the Earth follows a somewhat eccentric elliptical orbit around the sun with each annual revolution. The Earth's axial tilt in relation to its orbit is consistently  $23.5^{\circ}$ . The Earth's revolution remains constant as the orientation of its spin axis consistently points towards the North Pole. Consequently, the earth's orbital position alters the angle of sunlight incidence, resulting in the variation of the earth's seasonal fluctuations.
- At noon each day, the sun reaches its maximum elevation. In tropical low-latitude locations, specifically between the equatorial north and south latitudes of  $23^{\circ} 27'$ , sunlight experiences two vertical occurrences annually, but at higher latitudes, the sun remains consistently near the equatorial direction. In the Arctic and Antarctic regions (located in the northern and southern hemispheres beyond  $90^{\circ} \sim 23^{\circ} 27'$ ), the sun remains below the horizon for an extended duration throughout winter.

## 5.2 Diffuse and Direct Solar Radiation.

As sunlight traverses Earth's atmosphere, a portion is absorbed, dispersed, and reflected. Sunlight consists of two components: direct sunlight and diffuse sunlight. Solar radiation traverses the atmosphere and reaches the Earth's surface, influenced by atmospheric air molecules, water vapour, and dust, which contribute to the absorption, reflection, and scattering of solar radiation. This process not only diminishes the intensity of the radiation but also alters its direction and spectral distribution. Consequently, the solar energy that ultimately reaches the ground is typically comprised of direct and diffuse components. Direct sunlight refers to radiation emanating directly from the sun without alteration in its trajectory; diffusion involves the reflection and scattering of solar radiation by the atmosphere, resulting in a change of direction. This phenomenon comprises three components: circumsolar scattering (light surrounding the

sun), horizon circle scattering (light or darkness around the horizon), and additional diffuse radiation from the sky. Furthermore, the non-horizontal plane also captures the reflection of radiation from the earth. The total radiation or global sunlight is the aggregate of direct, diffuse, and reflected sunlight. It can depend on the lens or reflector to concentrate direct sunlight. A high condenser rate yields elevated energy density, but results in a loss of diffuse sunlight. A low condenser rate may also condense components of solar diffuse sunlight. Diffuse sunshine exhibits significant variability, and under cloudless conditions, it constitutes 10% of the total sunlight. When the sky is obscured by dark clouds and the sun is not seen, total sunshine is equivalent to diffuse sunlight. Consequently, a poly-type collector typically gathers energy at levels much beyond those of a non-poly-type collector. Reflected sunlight is typically feeble; but, over snow-covered terrain, vertical reflection can constitute up to 40% of the total sunshine.

### **5.3 Quantifying Sunlight and Solar Energy**

Researchers quantify the solar irradiance present in particular locales throughout various seasons. They can thereafter assess the quantity of sunlight that reaches analogous places at the same latitude with comparable temperatures and conditions. Solar energy measurements are typically articulated as "total radiation on a horizontal surface" or as "total radiation on a sun-tracking surface". In this scenario, it is presumed that a solar panel is employed that automatically follows the sun's trajectory. The solar panel would be affixed to a tracking mechanism to maintain a perpendicular orientation to the sun throughout the day. This system is predominantly utilised in industrial environments, if employed at all.

### **5.4 Measurements of Solar Energy**

Radiation data, which denotes the quantity of solar energy accessible at a specific place, for solar electric (photovoltaic) systems is often expressed in kilowatt-hours per square metre (kWh/m<sup>2</sup>). Direct measurements of solar energy can be articulated as "watts per square meter" (W/m<sup>2</sup>) (<https://www.energy.gov/eere/solar/articles/solar-radiation-basics>). Radiation data for solar water heating and space heating systems is often expressed in British thermal units per square foot (Btu/ft<sup>2</sup>).

## **6. PHOTOVOLTAIC MODULES**

A solar panel is an apparatus that captures and transforms solar energy into electricity or thermal energy. Solar photovoltaic panels can be constructed to harness solar energy, which energises the atoms within a silicon layer situated between two protective panels. Electrons from these energised atoms generate an electric current, which can be utilised by external devices. Solar panels were utilised over a century ago for residential water heating. Solar panels may also be constructed using a uniquely curved mirror that focusses light onto an oil-filled tube. The oil subsequently warms and passes into a vat of water, causing it to boil instantaneously. Steam is generated and subsequently drives a turbine to produce power.

### **6.1 Mechanism of Solar Panel Functionality**

The fundamental component of solar panels is pure silicon. When purified, silicon serves as an optimal neutral medium for electron transmission. Silicon, in its normal state, possesses four electrons but has the capacity for eight. Consequently, silicon can accommodate four additional electrons. When a silicon atom contacts another silicon atom, each atom acquires four electrons from the other. Eight electrons fulfil the atomic requirements, establishing a robust connection, however neither positive or negative charge is present. This substance is utilised in the fabrication of solar panel plates. The amalgamation of silicon with other charged components can potentially provide solar panels.

Phosphorus possesses five electrons available for donation to other atoms. The chemical

combination of silicon and phosphorus yields a stable configuration of eight electrons together with an extra free electron. The silicon does not require the free electron; nonetheless, it cannot depart due to its link with the adjacent phosphorus atom. Consequently, this silicon and phosphorus plate is regarded as negatively charged.

A positive charge must also be generated for the flow of electricity. The amalgamation of silicon with an element like boron, which possesses just three electrons to contribute, results in a positive charge. A silicon and boron plate retains one vacancy for an additional electron. Consequently, the plate possesses a positive charge. The two plates are juxtaposed to form solar panels, with conductive wires interspersed between them.

<http://www.articlesbase.com/technology-articles/solar-energy-basic-principles-649460.html>

Photons strike the silicon/phosphorus atoms when the negative plates of solar cells are orientated towards the sun. The ninth electron is ultimately ejected from the outer shell. The positive silicon/boron plate autonomously attracts the electron into the vacant region of its outer band, preventing the electron from remaining free for an extended duration. As the sun's rays dislodge additional electrons, electricity is subsequently produced. When all conductive lines extract free electrons from the plates, sufficient electricity is created to power low-amperage motors or other electronic devices, although the output of a single solar cell is quite modest. When electrons are not utilised or dissipated into the atmosphere, they are returned to the negative plate, and the complete cycle recommences.

## **6.2 Solar Thermal Energy**

sun thermal energy (STE) is a technology that captures sun energy for heating purposes. The US Energy Information Agency categorises solar thermal collectors as low, medium, or high temperature collectors. Low-temperature collectors are flat plates typically employed for heating swimming pools. Medium-temperature collectors, typically flat plates, are utilised for generating hot water for household and commercial applications. High-temperature collectors utilise mirrors or lenses to focus sunlight and are mostly employed for electricity generation. This differs from solar photovoltaic technology, which directly turns solar energy into electricity.

### **6.2.1 Low-Temperature Collector**

Sunlight penetrates the windows and impinges upon the absorber plate, which subsequently heats up, converting solar energy into thermal energy. Heat is conveyed to the liquid flowing through pipes connected to the absorber plate. Absorber plates are typically coated with "selective coatings," which exhibit superior heat absorption and retention compared to standard black paint. Absorber plates are generally composed of metal, commonly copper or aluminium, due to their excellent thermal conductivity. Copper is costlier; yet, it exhibits superior conductivity and reduced susceptibility to corrosion compared to aluminium. In areas with average solar energy availability, flat plate collectors are typically sized at around one-half to one square foot per gallon of daily hot water consumption.

This method is primarily utilised in residential structures, where hot water demand significantly influences energy expenses. This typically refers to a scenario involving a sizable family or one where the demand for hot water is heightened owing to regular laundry activities.

Commercial applications encompass automotive washing services, military laundry operations, and dining businesses. The method can furthermore serve for space heating in off-grid buildings or in instances when utility power is prone to frequent interruptions. Solar water heating systems are likely to be economically advantageous for facilities with costly water heating operations or for establishments such as laundries or kitchens that want substantial volumes of hot water.

Unglazed liquid collectors are frequently employed to heat water for swimming pools. Due to the absence of high-temperature requirements, these collectors can utilise more economical materials like plastic or rubber. They do not necessitate freeze-proofing, as swimming pools are often utilised solely in warm weather or may be simply drained during colder conditions. Although solar collectors are most economically viable in sunny, temperate regions, they can be financially advantageous in nearly every location across the country and should be taken into account.

### **6.2.2 Elevated-temperature collector**

To mitigate heat loss in flat-plate collectors and enhance collection temperature, the international community successfully developed vacuum tubes in the 1970s. The heat-absorbing element is encased in a high vacuum within the glass tube, significantly improving thermal efficiency. The assembly of multiple branch vacuum tubes shall form a vacuum tube collector, which is designed to enhance sunlight absorption; certain vacuum tubes are also equipped with reflectors at the rear. Vacuum collector tubes can be categorised into two main types: all-glass evacuated collector tubes (glass-U-tube vacuum collector tubes) and metal heat-pipe vacuum tubes (straight-through vacuum collector tubes and thermal storage vacuum collector tubes).

The condenser collector primarily consists of three primary components: the condenser, the absorber, and the tracking system. In accordance with the principle of distinction, condensers and condenser collectors can be classified into two categories: reflection and refraction condensers. Each category can further be subdivided into many types. To fulfil the demands of solar energy utilisation, such as streamlining tracking systems, enhancing reliability, and minimising costs through the development of condenser collectors in this century, various types of condenser collectors exist; however, their promotion is inferior to that of flat-plate collectors, resulting in a lower level of commercialisation. In reflecting concentrator collectors, the spinning parabolic mirror condenser (point focus) and the parabolic trough mirror condenser (line focus) are more commonly utilised. The former can become heated, while two-dimensional tracking is applicable; the latter can measure temperature, provided it is for one-dimensional tracking. The two types of condenser collectors were introduced at the beginning of this century and have undergone several enhancements over the decades, including the incorporation of reflective surfaces to enhance machining precision, the development of highly reflective materials, and the advancement of reliable tracking systems. Currently, these two varieties of parabolic trough collectors are fully equipped to satisfy diverse high-temperature solar energy utilisation demands; however, their elevated costs restrict broader application.

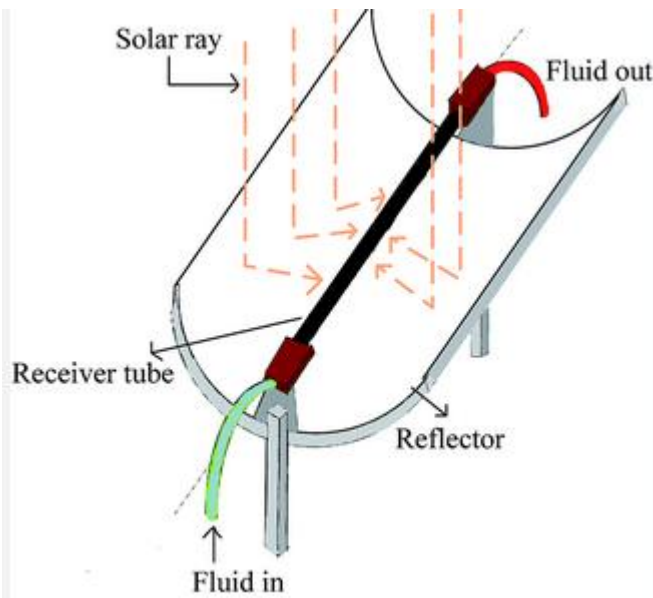
In the 1970s, the "compound parabolic concentrator mirror collector" (CPC) emerged on the international market. It comprises two parabolic mirrors; Concentrated Photovoltaic systems do not require solar tracking, merely seasonal changes, enabling them to gather sunlight and achieve elevated temperatures. The condensation rate typically remains below 10; when it falls below 3, it can be securely installed without requiring adjustments. At that time, many individuals highly regarded CPC, perceiving it as a significant advancement in solar thermal utilisation technology with potential for widespread application. Nevertheless, decades later, CPC has been utilised in only a limited number of demonstration projects and has not achieved widespread adoption like flat-plate collectors and vacuum tube collectors.

Other reflecting mirror concentrators include conical mirrors, spherical mirrors, bar mirrors, bucket-type trough mirrors, flat mirrors and parabolic mirror concentrators. Furthermore, a heliostat is utilised in a tower solar power plant. Heliostats have several flat or curved mirrors that, under computer control, direct sunlight to a single absorber, which can attain elevated temperatures and generate substantial energy.

The refraction theory of light allows for the creation of a refraction-type condenser. Certain individuals utilise a combination of lenses and flat mirrors to construct a high-temperature solar boiler. The glass lens is excessively heavy, the manufacturing process is intricate, and the cost is high, making it challenging to produce in larger sizes. Consequently, the refraction-type condenser is not a viable long-term solution. During the 1970s, the global advancement of big Fresnel lenses aimed to facilitate the construction of solar concentrating collectors. The Fresnel lens is a flat condenser lens that is lightweight and cost-effective, available in both spot and line focus configurations. It is typically constructed from plexiglass or other transparent plastics, but can also be produced from glass, primarily for use in solar concentrator power generation systems. The optical fibre condenser comprises fiber-optic lenses and optical fibres linked to solar composition, utilising an optical lens to focus light for office applications following fibre dispersion. The fluorescence condenser consists of a fluorescent pigment applied on a clear plate, often PMMA, which absorbs sunlight and certain fluorescent wavelengths within the absorption band, thereafter emitting fluorescence at a longer wavelength than the absorption band. Fluorescent emission undergoes total internal reflection at the edge face of the plate, attributable to the disparities between the plate and the surrounding medium. The condensation rate is contingent upon the ratio of flat area to edge area, achieving a ratio of 10:100 is feasible. This flat panel can capture sunlight from various angles and can also absorb diffuse light without necessitating solar tracking.

### 6.3 System Designs

The sun occupies several locations during the day. If the mirrors or lenses remain stationary, the focal point of the mirrors or lenses alters. Consequently, it appears imperative to implement a monitoring system that monitors the sun's location, while a solar tracker is merely optional for solar photovoltaics. The tracking method elevates expenses. Considering this, many designs can be identified based on their methods of concentrating light and tracking the sun's position.



**Figure 7.** Illustration of a parabolic trough configuration.

A parallel shift in the sun's position relative to the receiver does not necessitate mirror adjustment.

#### 6.3.1 Thermal Energy Storage.

##### 2.3.1.1 Thermal energy storage.

The utilisation of sensible heat energy storage materials constitutes the most straightforward storage option. In practice, water, sand, gravel, and soil can be regarded as materials for energy storage, with water being utilised more frequently due to its superior heat capacity. During the 1970s and 1980s, the utilisation of water and soil for interseasonal storage of solar energy was documented. However, the material exhibits low sensible heat, which constrains energy storage capabilities.

### **6.3.1.2 Latent Heat Storage**

Latent heat-storage units store thermal energy in a latent state by altering the phase of the storage medium. Relevant storage medium are referred to as "phase change materials" (PCM). Salts in crystalline form, such as sodium sulphate decahydrate, calcium chloride, and sodium hydrogen phosphate dodecahydrate, are typically utilised for low-temperature storage. We must address the cooling and layering challenges to maintain optimal operating temperature and service life.

The medium solar storage temperature typically exceeds 100°C; however, it is inappropriate for the medium temperature storage of the following materials:

- pressurized hot water,
- organic liquids,
- eutectic salt.

The temperature for solar heat storage typically exceeds 500°C. The specified materials, Liquid metal sodium and molten salt are presently undergoing evaluation for use in advanced nuclear reactor systems and concentrated solar power (CSP) plants that necessitate operation at exceptionally high temperatures. The exceptionally high temperature referenced (exceeding 1000°C) serves as a goal operating point for particular sophisticated designs.

### **6.3.2 Chemical and Thermal Energy Storage**

Thermal energy storage employs chemical reactions to retain heat. It possesses the advantages of substantial heat capacity, compact volume, and lightweight characteristics. The byproducts of a chemical reaction can be stored independently for an extended duration. An exothermic reaction happens when required. It must satisfy the following conditions to utilise chemical reactions in thermal storage: high reaction reversibility, absence of secondary reactions, quick kinetics, ease of product separation, and stability retention. The reactant and consequent are non-toxic, non-flammable, exhibit a high heat of reaction, and are cost-effective. Certain chemical endothermic reactions may satisfy the aforementioned requirements. Utilise the endothermic pyrolysis reaction of  $\text{Ca}(\text{OH})_2$  to store and subsequently release heat as needed. The temperature for the dehydration reaction under high air pressure exceeds 500 degrees. Utilising sun energy to facilitate dehydration reactions is challenging. A catalyst can be employed to reduce the reaction temperature, although it remains significantly elevated. The heat reserve in chemistry is now being testing.

### **6.3.3. Thermal energy storage utilising plastic crystals**

In 1984, the U.S. market introduced plastic crystal materials for residential heating. The technical designation of plastic crystal is Neopentyl Glycol (NPG); it shares similarities with three-dimensional periodic crystals, however its mechanical properties resemble those of plastic. It can store and release thermal energy at a constant temperature without relying on solid-liquid phase shift; instead, it utilises the solid-solid phase change within its plastic crystalline molecular structure to store energy. At a constant temperature of 44°C, plastic crystals absorb solar energy and store heat during the day, subsequently releasing it at night.

### **6.3.4 Solar Thermal Energy Storage Tank**

A solar pond is a specific type of salt pond characterised by a gradient of salt concentration, utilised for the collection and storage of solar energy. Due to its simplicity, affordability, and suitability for large-scale applications, it has garnered significant attention. Subsequent to the 1960s, other countries commenced research on solar ponds, and Israel constructed three solar pond power stations.

### **6.4 Levelized Cost**

Due to the absence of fuel utilisation in a solar power plant, the expenses primarily comprise construction costs, with little operational and maintenance costs. Provided that the plant's lifespan and the interest rate are known, the cost per kWh may be determined. This is referred to as the levelized cost. The initial stage in the calculation is to ascertain the investment required for the generation of 1 kWh annually. The information sheet for the Andasol 1 project indicates a total investment of 310 million euros for an annual production of 179 GWh. Given that 179 GWh equates to 179 million kWh, the investment per kWh of annual production is calculated as  $310 / 179 = 1.73$  euros. An other instance is the Cloncurry solar power station located in Australia. It generates 30 million kWh annually for an investment of 31 million Australian dollars. The cost is 1.03 Australian dollars for the generation of 1 kWh annually. This is considerably less expensive than Andasol 1, which can be partially attributed to the greater radiation in Cloncurry compared to Spain. The annual investment cost per kWh should not be conflated with the total cost per kWh during the whole lifespan of the plant.

Typically, the capacity of a power plant is designated, as exemplified by Andasol 1, which has a capacity of 50 MW. This figure is inappropriate for comparison because to variations in the capacity factor. A solar power plant equipped with heat storage can generate output post-sunset; however, this does not alter the capacity factor, it merely shifts the output. The average capacity factor for a solar power plant, influenced by tracking, shade, and location, is approximately 20%. Consequently, a 50 MW capacity power plant will generally yield an annual output of  $50 \text{ MW} \times 24 \text{ hours} \times 365 \text{ days} \times 20\% = 87,600 \text{ MWh/year}$ , equivalent to 87.6 GWh/year.

While the investment for one kWh of annual production is appropriate for comparing the costs of various solar power plants, it does not provide the price per kWh. The method of financing significantly impacts the final price. Should the technology be validated, a 7% interest rate should be attainable. Nevertheless, for emerging technologies, investors want a much-elevated return to offset the increased risk. This substantially adversely impacts the price per kWh. Regardless of the financing method, a linear relationship consistently exists between the annual investment per kWh produced and the price of one kWh (excluding operational and maintenance costs). Consequently, if technological advancements result in a 20% reduction in investments, the price per kWh will similarly decrease by 20%.

In a financing scenario where funds are borrowed and repaid annually, resulting in a reduction of both principal and interest, the division factor can be calculated using the formula:  $(1 - (1 + \text{interest} / 100)^{-\text{lifetime}}) / (\text{interest} / 100)$ . For a duration of 25 years and an interest rate of 7%, the division factor is 11.65. The investment for Andasol 1 was 1.73 euros; when divided by 11.65, this yields a cost of 0.15 euros per kWh. Incorporating a one cent operating and maintenance cost results in a levelized cost of 0.16 euros. Alternative funding methods, varied debt repayment strategies, differing life expectancies, and distinct interest rates may result in a substantially different outcome.

If the cost per kWh correlates with inflation, the inflation rate can be incorporated into the interest rate. If an investor deposits funds in a bank at a 7% interest rate, he is not adequately paid for

inflation. Nevertheless, if the cost per kWh increases with inflation, he gets reimbursed and can incorporate a 2% adjustment (a standard inflation rate) into his return. The Andasol 1 facility is assured a feed-in tariff of 0.21 euros for a duration of 25 years. If this figure remains constant, it should be acknowledged that after 25 years of 2% inflation, 0.21 euro will possess a value equivalent to 0.13 euro now.

Ultimately, a delay exists between the initial investment and the commencement of electricity production. This enhances the investment with the interest during the period when the plant is inactive. The modular solar dish, together with solar photovoltaic and wind power, offers the benefit of initiating electricity production immediately upon completion of construction.

Considering that solar thermal power is dependable, capable of providing peak demand, and environmentally benign, a price of US\$0.10 per kWh begins to be competitive. While a price of US\$0.06 has been asserted with some operating expenses, a straightforward objective is to achieve an investment of 1 dollar (or less) for the production of 1 kWh annually.

### 6.5. Types of solar panels

Decades of study, labour, and innovation have resulted in a diverse array of solar panel types currently accessible in the market.

Table 1 presents an overview of the most prevalent and distinctive types of solar panels.

**Table 1.** Types of solar panels

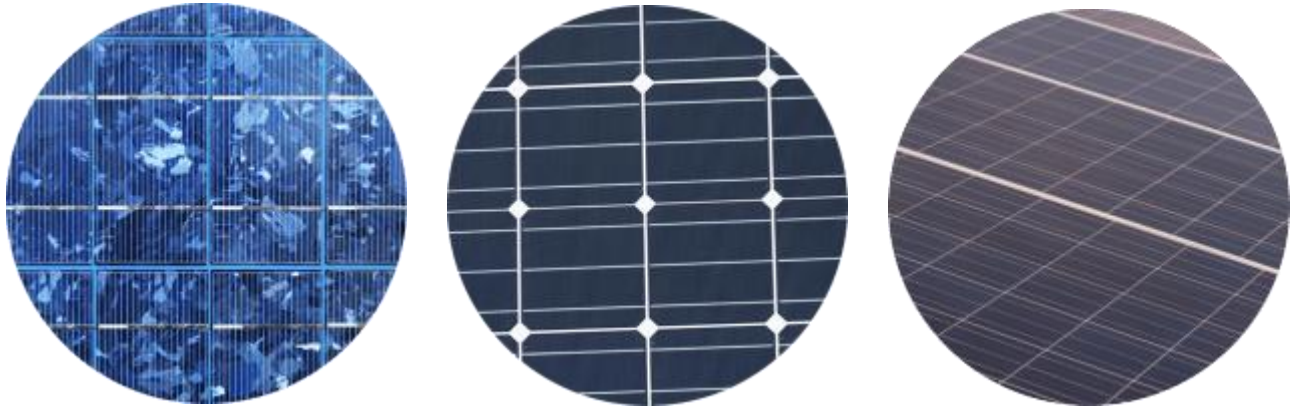
Solar Cell Type	Efficiency-Rate	Advantages	Disadvantages
Monocrystalline Solar Panels (Mono-SI)	~20%	High efficiency rate; optimised for commercial use; high life-time value	Expensive
Polycrystalline Solar Panels (p-Si)	~15%	Lower price	Sensitive to high temperatures; lower lifespan & slightly less space efficiency
Thin-Film: Amorphous Silicon Solar Panels (A-SI)	~7-10%	Relatively low costs; easy to produce & flexible	shorter warranties & lifespan
Concentrated PV Cell (CVP)	~41%	Very high performance & efficiency rate	Solar tracker & cooling system needed (to reach high efficiency rate)

(source, <https://www.greenmatch.co.uk/blog/2015/09/types-of-solar-panels>)

#### 6.5.1 Methods for Classifying Various Types of Solar Panels

The utilisation of sunlight varies significantly between Earth and space, indicating that location is a crucial determinant in selecting among different types of solar panels. Differentiation among solar panels typically involves distinguishing between single-junction and multi-junction panels, as well as categorising them into first, second, or third generations. Single-junction and multi-junction panels are differentiated by the number of layers that capture sunlight, while generational classification emphasises the materials and efficiency of the various solar panel types.

The 1st Generation Solar Panels are conventional forms composed of monocrystalline silicon or polysilicon, widely utilised in standard environments.



**Figure 8.** Types of Solar Panels

Monocrystalline (left), Polycrystalline (centre), Thin-Film Solar Cells (right) (source: <https://www.greenmatch.co.uk/blog/2015/09/types-of-solar-panels>)

#### *Monocrystalline Silicon Solar Panels (Mono-SI)*

This category of solar panels, composed of monocrystalline silicon, represents the highest purity. They can be readily identified by their uniform black appearance and rounded edges. The great purity of silicon results in this type of solar panel achieving one of the highest efficiency rates, with the latest models exceeding 20%. Monocrystalline panels have superior power output, use little space, and has the longest lifespan. Consequently, they are the priciest among the group. Another advantage to consider is that they are generally less impacted by elevated temperatures in comparison to polycrystalline panels.

#### *Polycrystalline Solar Panels (Poly-SI)*

These panels can be readily identified due to their square shape, uncut angles, and blue, speckled appearance. They are produced by melting raw silicon, a procedure that is more expedient and cost-effective than that employed for monocrystalline panels. This results in a reduced end price, but also diminished efficiency (about 15%), less spatial efficiency, and a shorter lifespan due to greater susceptibility to elevated temperatures. The distinctions between monocrystalline and polycrystalline solar panels are minimal, and the selection will mostly depend on your particular circumstances. The initial alternative provides somewhat greater space efficiency at a marginally elevated cost, while the power outputs remain fundamentally equivalent.

#### *Second Generation Solar Panels*

These cells represent many forms of thin film solar cells, primarily utilised in photovoltaic power plants, integrated within buildings or smaller solar power systems.

#### *Thin-Film Solar Cells (TFSC)*

If you seek a more economical alternative, consider thin-film technology. Thin-film solar panels are produced by depositing one or more layers of photovoltaic material, such as silicon, cadmium, or copper, onto a substrate. These solar panels are the simplest to manufacture, and economies of scale render them more cost-effective than alternatives due to reduced material requirements for production.

They exhibit flexibility, which creates numerous potential for alternate applications, and are less susceptible to elevated temperatures. The primary concern is their substantial spatial

requirements, rendering them often inappropriate for residential use. Furthermore, they possess the briefest guarantees due to their reduced lifespan compared to mono- and polycrystalline solar panels. Nevertheless, they may be a viable choice among the various forms of solar panels when ample space is accessible.

#### *Amorphous Silicon Photovoltaic Cell (A-Si)*

Have you ever utilised a solar-powered pocket calculator? Affirmative? You have certainly encountered these varieties of solar panels already. The amorphous silicon solar cell is primarily utilised in pocket calculators among the several varieties of solar panels. This solar panel employs a triple-layered technology, representing the pinnacle of thin-film varieties. In this context, "thin" refers to a thickness of 1 micrometre (one millionth of a metre). These cells exhibit a mere 7% efficiency, rendering them less effective than crystalline silicon cells, which achieve approximately 18% efficiency; however, the advantage lies in the relatively inexpensive cost of A-Si cells.

#### *Third Generation Solar Panels*

Third-generation solar panels encompass many thin-film technologies, the majority of which remain in the research or development stage. Some create energy utilising organic materials, while others employ inorganic compounds, such as CdTe.

#### *Biohybrid Solar Cell*

The Biohybrid solar cell is a form of solar panel currently in the research phase. An elite team at Vanderbilt University has made a discovery. The concept of the new technology is to leverage photosystem 1 to replicate the natural process of photosynthesis. It elucidates in greater depth the functioning of these cells. The materials utilised in this cell resemble those of conventional approaches; however, by integrating multiple layers of photosystem 1, the conversion of chemical to electrical energy is significantly enhanced, achieving efficiency levels up to 1000 times greater than first-generation solar panels.

#### *Cadmium Telluride Photovoltaic Cell (CdTe)*

This photovoltaic method employs Cadmium Telluride, facilitating the manufacture of solar cells at a comparatively low cost and resulting in a payback period of less than one year. Among all solar energy systems, this one necessitates the minimal water use for manufacturing. Considering the brief energy payback period, CdTe solar cells will minimise your carbon footprint.

The sole drawback of utilising Cadmium Telluride is its inherent toxicity when swallowed or inhaled. In Europe, this represents a significant obstacle, as numerous individuals express considerable apprehension regarding the technology underlying this form of solar panel (<https://www.greenmatch.co.uk/blog/2015/09/types-of-solar-panels>).

#### *Concentrated Photovoltaic Cell (CPV and HCPV)*

Concentrated photovoltaic cells produce electrical energy in the same manner as traditional solar systems. Multi-junction solar panels exhibit an efficiency rate of up to 41%, the highest recorded among all photovoltaic systems to date. The designation of these CVP cells pertains to their exceptional efficiency relative to other solar panel types: they utilise curved mirror surfaces, lenses, and occasionally cooling systems to concentrate sunlight, thereby enhancing their performance.

Consequently, CVP cells have emerged as one of the most effective varieties of solar panels, with a performance and efficiency rate of up to 41%. The efficiency of CVP solar panels is contingent upon their orientation towards the sun at an optimal angle. A solar tracker within the solar panel is responsible for following the sun to achieve high efficiency rates (Misak et al.,

2016).

## 7. APPLICATIONS OF SOLAR ENERGY

Solar energy, harnessed from the sun via solar panels, represents a recent endeavour of the "Going Green" movement aimed at establishing and sustaining renewable energy sources. Similar to any new home addition, there are initial expenses associated with the components and installation required to operationalise it (<https://www.thespruce.com/top-solar-energy-uses-1152263>).

### 7.1 Solar-powered Ventilation



**Photo 1** Solar power ventilation

(source, <https://eurzad.brodnicapl/?d=118173634081890>)

How would you prefer to utilise solar energy to operate bath fans, floor fans and ceiling fans in your residence? Fans are extensively employed within households to facilitate air circulation for comfort, humidity control and odour management. Consider the heating and cooling dynamics in your home and the potential reduction in utility expenses. Reflect on the number of ceiling fans that operate daily in your residence. Additionally, contemplate the frequency of bath fan usage throughout the day.

### 7.2 Utilise Solar Energy to Heat Your Swimming Pool



**Figure 9.** Swimming Pool Heating (Source: <https://www.theengineeringchoice.com/what-is-solar-pool-heater/>)

Swimming pools represent one of the paramount delights of summer for both children and parents. All are enthusiastic on the inaugural day of the pool's opening, except when the water temperature is excessively frigid for entry. To resolve that issue, you may incorporate a solar blanket that will heat the water, much to the satisfaction of all. This heating operates directly via the blanket, requiring no additional installations. However, if you choose to use a more advanced approach, simply install a solar hot water heating system. This system employs solar hot water heating panels affixed to your roof to capture solar

energy, which is subsequently circulated to the pool. The pool temperature is elevated when water is gradually extracted, heated, and subsequently returned from the panels.

### 7.3 Solar energy has the capacity to heat water.

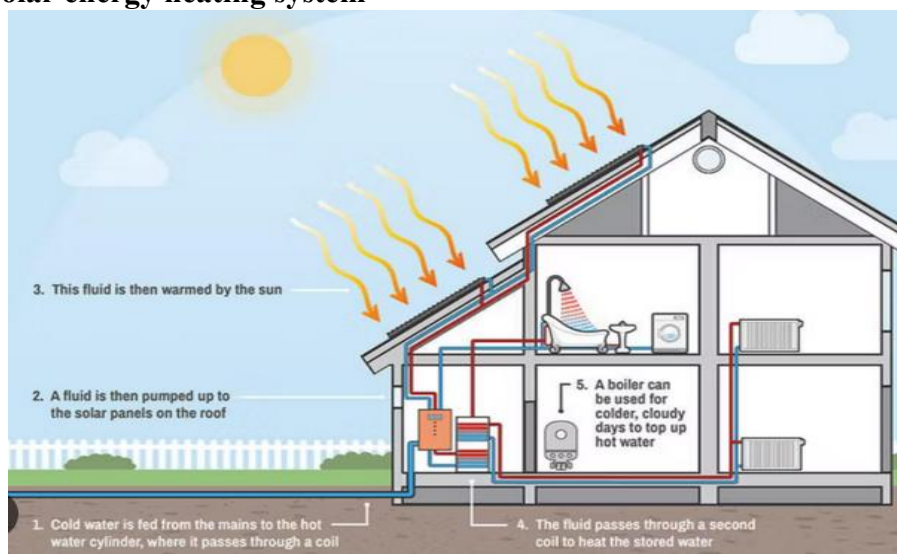


**Figure 10.** Solar Water Heaters Source: <https://bluebirdsolar.com/blogs/all/solar-water-heater-the-smart-way-to-heat-water-using-the-power-of-the-sun?srltid=AfmBOoolR4jVczOdCBhRL6j1PRkzIQZNtWk2yIb4WGYweiJVJ76Zr3zM>

Have you contemplated the feasibility of utilising solar energy for water heating instead of relying on gas or traditional electric water heaters? I understand you can assert that acquiring all these components is necessary for this choice to function. Installation may be feasible for you or may not. Considering the expense, it may be prudent to retain your current option, correct?

Proceed with caution! Upon reflection, it is analogous to replacing an obsolete furnace, water heater, or air conditioning equipment. Replacing the unit may enhance efficiency by 15-30%, albeit this modification entails an initial expenditure. While the alteration will result in long-term financial savings, this should be evaluated over an extended timeframe.

### 7.4 Solar energy heating system



**Figure 11.** Solar heating system for roofs (source: <https://www.screwfix.com/guides/heating-plumbing/renewable-heating/solar-water-heating-guide>)

Solar heating is known as passive space heating, and in this instance, I will elucidate its functioning. A method involves utilising hot water heating in your residence, generated by sun-

heated tubes on your roof, which are then pumped into your water heater (<https://www.thespruce.com/top-solar-energy-uses-1152263>).

The inclusion of a sunroom, termed a solar room, features an all-glass structure that permits sunlight to permeate and warm the space via a collector known as a transparent covering in the glass. Incorporating plants and rocks for aesthetic appeal will enable the rocks to absorb solar heat, which can subsequently be utilised to warm the room after sunset. Stored energy is advantageous and has numerous applications, such as batteries, for example.

### **7.5 Solar energy-powered pumps**



**Figure. 12** Solar Pump (Source: <https://www.samkingpump.com/product/4spw4-3p-600w>; <https://www.whcsolar.cc/product/1100w-solar-surface-water-pump/> )

In the two preceding illustrations, water was utilised for heating both water and your residence. To achieve that duty, you'll need to have a pump to circulate the water around. This pump would ordinarily connect to your home's power source, but let me give you this helpful suggestion. You can utilise solar energy to drive a DC motor that will slowly circulate the water throughout your home or in and out of your water heater. This way, the cost of the system is decreased further. Now, the naysayers may say fantastic, but what do we do when there is no sun? One way is to have conventional power run a pump when there is no sun. You can also have a battery backup system that can run the pump and the battery might be connected to a solar battery charger.

### **7.6 Solar energy for battery charging**

Have you considered solar energy for charging batteries? These could be utilised to power sump pumps, hot water pumps, ceiling fans in your home, or lighting that is of DC nature. Battery chargers are utilised in houses to charge all of those batteries used for video games and such as well. But most likely, if you have a reserve battery bank that is charged through the day while sunlight is present and is used for the nocturnal hours, you can see the benefits of that, right?

### **7.7 Use solar energy to power your home**

Indeed, solar energy has the capacity to power your residence. The required system is not overly complex when reviewing the necessary equipment. Install solar panels to harness sunlight and transform it into electricity. Direct current (DC) power is transmitted to an inverter, which transforms it into alternating current (AC) power that operates your home. Utilising transfer switches and additional safety mechanisms, your clean, renewable energy source can supply power to your home, camper, cabin, tool shed, or any other structure.

### 7.8 Solar energy utilised for culinary purposes



**Figure 14.** Solar Stove & Solar PV Cook-stove:

Source: (<https://www.engineeringforchange.org/solutions/product/solar-pv-cook-stove/>)

This is universally relatable. Ultimately, sustenance is a must for everyone. The energy and resources expended on cooking may lead to unexpected utility expenditures. Utilising solar energy for cooking is far simpler than one might assume. We refer to it as thinking outside the box, or in this instance, cooking within a box. Envision utilising a solar oven for cooking rather than your traditional home appliance. Constructing one of these is a formula for great culinary endeavours on sunny days! Equipped with a box, pan, aluminium foil, a cooking bag, duct tape, styrofoam insulation and a thermometer, you will be able to cook promptly.

### 7.9 Photovoltaic Energy for Interior Illumination



**Figure 15.** Indoor Lighting (source: <https://insolitehardware.com/product/baxton-50w-indoor-solar-light/>)

Illumination throughout your residence is a universal necessity. The advent of LEDs (light emitting diodes) enables your home to provide ideal illumination with little energy consumption. These little electronic lights or light assemblies can be linked to a battery-operated system that

harnesses solar energy during the day and utilises batteries at night. When sunlight is present, the battery charger replenishes the backup battery and powers the illumination. Subsequently, at night, the batteries activate and provide illumination in the absence of sunlight.

### **7.10 Utilisation of solar energy for outside illumination**



**Figure 16.** Outdoor lighting (source: <https://www.streetlights-solar.com/popularity-solar-outdoor-lighting-us.html>)

If you share my preference, you appreciate returning home at night to the presence of security lighting and illuminated pathways. It not only provides a clear view of the walkway, keys, and entrance door, but also acts as a deterrent to intruders. Similar to a pole light, your entire yard can be illuminated at no cost. Indeed, solar lighting utilises solar panels to charge batteries during daylight, which subsequently power the lights at night.

### **7.11 Drawbacks of solar energy**

Given the annual increase in electricity costs of 3%-5%, you might be contemplating alternate energy sources, such as solar power. However, prior to installing a solar system on your residence, several significant disadvantages must be considered. Given that solar power incurs the highest starting costs among all renewable energy sources, one may expect it to be highly effective. In actuality, solar panels exhibit low efficiency. In a prime location, achieving a conversion rate of 22% is fortunate, even with the most advanced and costly technologies accessible. Additionally, solar panels may be susceptible to damage from storms. In addition to the expense of repairing the solar panels, the damaged units must be managed and disposed of appropriately due to the hazardous substances contained within.

### **7.12 Geographical position and solar exposure**

Your latitude significantly influences the effectiveness of solar power. Annual sunlight distribution varies by location, with solar power efficiency significantly diminishing as one move away from the equator. This indicates that inhabitants in regions such as Canada and Russia experience a solar disadvantage. In regions such as Hawaii, which experience an average of 277 days of rain and cloud cover annually, their proximity to the equator is inconsequential due to insufficient unobstructed sunshine reaching the surface.

<http://waldenlabs.com/disadvantages-solar-energy>

The effectiveness of solar energy is also influenced by the season. During the summer, you can produce more electricity than required due to the sun's proximity to your location. During winter, the sun's angle is more oblique relative to your position, resulting in insufficient electricity generation to meet your demands. Similar to all objects exposed to sunlight, solar panels will experience degradation due to ultraviolet radiation. Elements such as wind, hail, snow, debris, and temperature variations pose significant risks to solar panels.

### **7.13 Installation Zone**

For homes seeking to install solar panels, the installation space is often not a significant concern, particularly as they are predominantly affixed to the roof. Nonetheless, large corporations aiming to generate substantial power will require an extensive installation area to ensure regular electricity supply. The largest solar farm, situated in Spain, spans over 173 acres and supplies energy to nearly 12,000 houses. That constitutes 173 acres of land that cannot be utilised for any other purpose, such as grazing livestock.

<https://www.nachi.org/disadvantages-solar-energy.htm?loadbetadesign=0>

### **7.14 Dependability**

As solar energy is dependent on sunlight, electricity generation is not possible at night, necessitating the storage of surplus energy produced during the day or the connection to an alternative power source, such as the local utility grid. This indicates that you will incur additional expenses above the elevated price of the solar panels. Clouds and storms impede energy production by obstructing light rays that might otherwise be absorbed by the solar panel.

### **7.15 Ineffectiveness**

The Qualitative Reasoning Group at Northwestern University indicates that the majority of residential solar panels convert merely 14% of their accessible energy into electricity. Contemporary solar panels, even at peak efficiency, convert merely 22% of available energy into electricity. The second rule of thermodynamics dictates that solar cells cannot achieve 100% efficiency. The optimal theoretical maximum efficiency is 85%, achievable with mirrors and motors that track the sun. The maximum theoretical efficiency for a non-tracking system is limited to 55%. This also applies to systems that monitor the sun under overcast conditions. While solar energy can still be harvested during overcast and rainy days, the effectiveness of the solar system diminishes. Solar panels rely on sunlight to efficiently collect solar energy. Consequently, several overcast, rainy days can significantly impact the energy grid. It is essential to consider that solar energy cannot be harvested at night. Conversely, if your water heating solution must operate at night or throughout winter, thermodynamic panels are a viable choice.

### **7.16 Environmental pollution and its consequences**

Solar energy impactors can be temporally classified throughout the lifespan of a photovoltaic (PV) or concentrating solar power (CSP) system, from construction to decommissioning, and may exert one or more potential effects on the environment, eliciting various ecological responses. The technology, dimensions, and placement of solar energy infrastructure may affect biota and the environment in several manners. Integrated solar energy refers to energy that incurs no land-use or land-cover changes beyond those related to the extraction of raw materials and production processes. Consequently, it has negligible to no detrimental impacts on the ecosystem (apart from life-cycle emissions), resources (such as cultural assets), and legal rights, including the religious rights of indigenous populations. Integrated solar energy is systematically incorporated into components of the built environment in urban and suburban locales, such as commercial and residential rooftops, parking garages, and carports, in proximity to consumers. Despite its geographical dispersion, integrated solar energy presents significant solar energy

potential, with estimates indicating that 20%–27% of all residential rooftop areas and 60%–65% of commercial rooftops in the United States are suitable for photovoltaic and solar thermal systems. Conversely, displacing solar energy entails supplementary land-use or land-cover alterations, so diminishing biophysical capacity or enabling the depletion of other valuable resources (e.g., cultural) over the Earth's surface. These installations are generally ground-mounted and possess substantial capacity. They are frequently situated at considerable distances from demand loads and existing transmission infrastructure, necessitating extensive land area (i.e., installed capacity increases in tandem with land area) (Murphy-Mariscal Michelle L. et al., 2018).

### **7.17 Land Specifications**

To satisfy anticipated energy consumption requirements by 2040, it is expected that almost 800,000 km<sup>2</sup> of extra land (with spacing), an area twice the size of California, will be impacted by carbon-intensive and renewable energy production. Ground-mounted solar energy necessitates substantial land areas to accommodate power plant infrastructure, mirrors and towers (e.g., CSP), and panels (e.g., PV), resulting in these installations frequently being located at considerable distances from urban population centres, where electricity consumption is highest. This may require supplementary transmission infrastructure (e.g., power line corridors, roadways, and substations) to convey electricity, hence extending consequences beyond the immediate footprint of the facilities (Murphy-Mariscal Michelle L. et al., 2018).

The environmental consequences of solar power include land and water use, pollution, habitat destruction, and the employment of very toxic substances in the manufacturing process.

Reflecting on the installation area, the land utilisation for solar fields might be extensive, and unlike wind power, co-utilization for agricultural purposes is not feasible. Solar power influences land utilisation concerning the extraction and manufacturing of materials required for photovoltaic output.

Solar panels include cadmium and lead, both of which are highly dangerous elements. Various harmful and hazardous substances utilised in solar panel production include gallium arsenide, copper-indium-gallium-diselenide, hydrochloric acid, sulphuric acid, nitric acid, hydrogen fluoride, 1,1,1-trichloroethane, and acetone. In the United States, manufacturers are mandated to ensure that certain high-value compounds are recycled instead than discarded. In nations like China, Malaysia, the Philippines, and Taiwan, where more than fifty percent of photovoltaics are produced, hazardous materials are being carelessly discarded in fields, contaminating the air, water, and land.

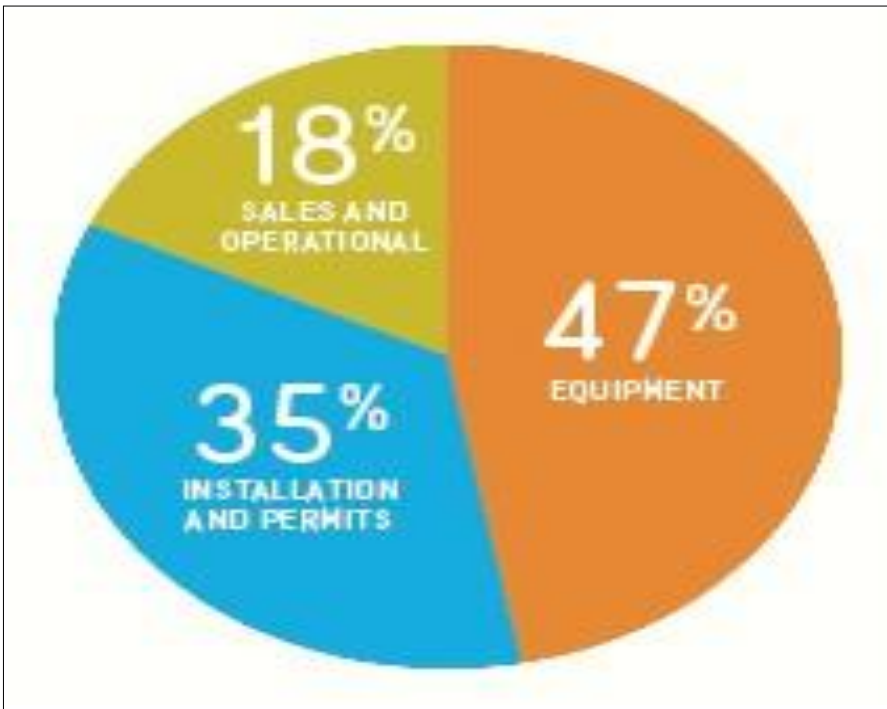
### **7.18 Costly energy storage**

The major challenge in generating solar electricity on an industrial scale is widely regarded as the storage of substantial quantities of electrical energy. The existing battery storage systems for converting solar energy into electrical energy are prohibitively costly. Tesla has developed the Powerwall battery to accumulate solar energy for subsequent utilisation. Nonetheless, a 14kWh battery, priced at approximately \$7,100 including installation, is quite costly. To provide one day's worth of backup electricity for a four-bedroom house, three Tesla batteries would be required, resulting in a substantial total cost.

\$18,300.

### **7.19 Substantial upfront expenditure**

The cost for average-sized systems generating between 4kW and 8kW of power ranges from \$15,000 to \$29,000. The expenses encompass solar panels, inverters, mounting gear, wiring, installation, permits, repairs, monitoring and maintenance, as well as supplementary operational and overhead costs.



**Figure 17.** Percentages of measured costs of solar panels acquisition (source, <https://www.sunrun.com/solar-lease/cost-of-solar>)

Solar panels are quantified in watts and typically priced in dollars per watt. Not all panels possess the same quality, and their pricing reflects this disparity. Equipment expenses encompass solar panels, inverters, mounting hardware, and wiring; installation and permits include solar installation, supply chain logistics, permitting, and interconnection; sales and operational costs comprise monitoring and maintenance expenses, repairs, and supplementary operations and administrative expenditures. This does not encompass a battery storage system, which incurs an additional expense. Battery storage solutions are unnecessary if you want to meet your energy requirements by connecting to the local electricity grid.

Considering the expense of a battery storage system as previously outlined, the estimated total cost ranges from \$33,300 to \$47,300 to consistently provide sufficient energy, both day and night, for the typical four-bedroom residence. Depending on the climate and your geographical location, you may need to curtail usage and exercise greater frugality in your energy consumption.

Another aspect to evaluate regarding the initial expenditure is the payback period. For a \$18,000 system, a payback period of 20 years is anticipated based on the savings generated by solar electricity. That is not particularly rational for the majority of individuals and their financial circumstances.

### **7.20 Financial Disadvantages**

The primary drawback of solar energy is its economic feasibility. The semiconductor materials used in the production of solar cells are too costly to manufacture. Despite advancements in materials science and manufacturing techniques, the core methods remain prohibitively expensive. Less expensive solar panel materials are utilised in consumer electronics; nevertheless, they produce significantly lower power output compared to traditional photovoltaic

cells.

Recent findings enable the utilisation of a broader spectrum of solar energy for power generation; nevertheless, these experimental materials still rely on costly crystal growth and doping techniques. Advancements in manufacturing remain some decades distant. For several decades, solar power producing facilities have functioned under government sponsorship, demonstrating that harnessing electricity from solar energy is technically feasible, albeit economically unviable, at least for the time being. These installations are situated in sparsely inhabited, arid areas that see nearly constant sunlight throughout the year. Extensive tracts of affordable land are necessary to house the solar panels and mirrors, necessitating the placement of these power plants at considerable distances from the sites of energy consumption. Costly transmission towers must bridge the gap between remote power sources and energy-consuming urban centres.

Notwithstanding the existing drawbacks of solar power, utilising the sun's free energy remains promise. As scientific advancements and manufacturing methods enhance the efficiency and reduce the cost of solar cells, solar power will emerge as a significant energy source for residential properties in the future.

## **8. CONCLUSION**

The sun remains the most abundant, reliable, and long-lasting energy source available to humanity, and understanding its mechanisms—from nuclear fusion at its core to the dynamics of solar radiation reaching Earth—is fundamental to advancing modern energy systems. The scientific evolution from early misconceptions of chemical combustion and gravitational contraction to the correct explanation of nuclear fusion has enabled the development of sophisticated solar energy technologies capable of harnessing this immense resource. The proton–proton chain reaction, the transformation of mass into energy, and the binding energy of helium nuclei collectively illustrate the extraordinary physical processes that sustain the sun's luminosity and ensure its stability over billions of years.

Solar energy technologies, particularly photovoltaic and solar thermal systems, translate the sun's radiation into practical heating and electricity solutions. Advances in semiconductor engineering, thin-film materials, and high-efficiency concentrated PV systems demonstrate the vast potential of solar power as a cornerstone of global energy transformation. Meanwhile, thermal energy storage systems, including molten salts, phase-change materials, and emerging chemical storage pathways, address intermittency limitations and enhance the reliability of solar-driven electricity generation.

At the global scale, solar energy has become the fastest-growing renewable energy source, driven by declining costs, technological innovation, and urgent climate imperatives. Forecasts by international energy agencies demonstrate unprecedented expansion, with solar PV expected to dominate global renewable capacity additions through 2030. Nevertheless, challenges persist. These include land-use requirements, environmental impacts from manufacturing and disposal, supply chain concentration, energy storage costs, and the structural need for flexible, modernised power grids.

Despite these obstacles, ongoing research in materials science, energy storage, and solar fuels continues to improve efficiency, reduce economic barriers, and minimise environmental footprint. The exploration of advanced semiconductor structures, biohybrid photovoltaic systems, thermochemical storage cycles, and synthetic solar fuels holds promise for a future in which solar energy becomes not only a supplementary resource but a primary driver of global power systems.

Ultimately, solar energy stands at the intersection of scientific discovery, technological innovation, and environmental necessity. Its continued development is essential for meeting global energy demands, reducing dependence on fossil fuels, enhancing energy security, and mitigating the impacts of climate change. While considerable progress is still required to make solar power universally accessible, economically competitive, and environmentally sustainable, its potential remains unmatched. With sustained research, supportive policies, and strategic investments, solar energy will continue to shape the foundation of a cleaner, more resilient, and more sustainable global 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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## AN OVERVIEW OF THE TOOLS & TECHNIQUES FOR PV SYSTEM OPERATIONS & MAINTENANCE

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### ABSTRACT

*This paper provides a comprehensive overview of photovoltaic (PV) technology, its historical evolution, operational principles, and the modern engineering significance of solar energy systems. It begins by explaining the fundamentals of the photovoltaic effect, solar radiation, and semiconductor physics, emphasizing the roles of intrinsic and extrinsic semiconductors, P–N junctions, and electron–photon interactions that enable electricity generation. Various PV cell technologies—monocrystalline, polycrystalline, and thin-film—are examined, highlighting their performance characteristics, efficiency metrics, and suitability for different applications. A historical timeline traces major developments from Becquerel’s discovery of the photovoltaic effect in 1839 to recent advancements such as transparent solar cells and high-efficiency tandem technologies. The paper further explores the growing importance of PV systems in modern engineering, focusing on their contributions to climate change mitigation, energy security, economic development, and infrastructure resilience. Real-world examples illustrate the integration of PV across residential, commercial, and utility-scale projects. A major section presents an in-depth discussion of operations and maintenance (O&M).*

### 1. INTRODUCTION

For most of its history, most photovoltaics (PV) Industry has focused on the development of PV module technology, inverters, components, and manufacturing. These efforts have helped to advance the state of the art for PV systems worldwide. In light of this growth and the continued maturation of the PV market, the industry must focus on operating and maintaining systems. PV installation life- times are expected to be 25 years or more, so safe and proper maintenance is an integral part of successful and reliable operation. System operations and maintenance (O&M) is a broad area, and is the continuing focus of several industry/ government/national laboratory working groups. These groups will better define the issues and develop consensus O&M approaches over the next few years. In the interim, Solar ABCs has prepared an

O&M introductory report that includes practical guidelines for PV system maintenance and options for inspection practices for grounded PV systems. It is intended for mono-polar, grid-connected PV systems, and does not explicitly cover bi-polar, ungrounded, stand-alone, or battery backup systems. Off-grid systems have many of the same components, however, and portions of the guidelines can be used for inspection or maintenance of off-grid systems.

## **2. QUALIFIED PERSONNEL**

This paper is intended to help qualified individuals maintain and inspect PV systems safely. The U.S. Department of Labor's Occupational Safety and Health Administration (OSHA) defines a qualified person as one who has received training and has demonstrated skills and knowledge in the construction and operation of electrical equipment and installations and the hazards involved. Technicians can be qualified for some maintenance and service tasks but still be unqualified for others. Whether someone is a "qualified person" often depends on the specifics of the task at hand.

Qualification is earned by either direct on-the-job training under qualified supervision or through training programs offered by accredited educational institutions or manufacturers. Many testing and maintenance activities require two people to be completed safely and efficiently. An employee who is being trained for a task, demonstrates the ability to perform duties related to that task safely, and is under the direct supervision of a qualified person is usually considered to be a qualified person.

Additionally, in order to be considered a qualified person for PV service and maintenance, a person must be trained in and familiar with:

- the skills and techniques necessary to identify exposed live parts from other parts of electrical equipment,
- the skills and techniques necessary to determine the nominal voltage of exposed live parts,
- the clearance distances specified by OSHA in the Code of Federal Regulations (CFR) Part 1910.333(c) ("Working on or near energized parts") and the corresponding voltages to which the qualified person will be exposed,
- the characteristics of PV sources and hardware typically used in PV systems, and
- the characteristics of the hardware used in the PV system the person is working on.

It is strongly recommended that anyone working around energized PV systems complete a minimum of the 10-hour OSHA-10 Construction Industry Training Program. Local jurisdictions may specify the necessary training, skills, certifications, or licenses required to perform the work discussed in this report. One indicator that a person may be qualified to work on many types of PV systems is to confirm that the person is a certified energy practitioner who has met the qualifications for and passed a certification exam.

## **3. SAFETY REQUIREMENTS**

Safety begins with adequate planning and preparation. Effective safety policies must be in place and employees and contractors must be familiar with—and committed to following—safety procedures in order to prevent accident or injury. Major safety requirements during PV servicing include the proper use of lockout/ tagout procedures,

the use of personal protective equipment (PPE), procedures for safely disconnecting live circuits, and appropriate observation of and compliance with all PV-specific system signage and warnings.

### **3.1 Lockout/Tagout**

Lockout/tagout (LOTO) procedures are designed to ensure safe working practices and must be strictly followed whenever systems are de-energized prior to servicing. LOTO is covered by CFR, under 29 CFR 1910.147. LOTO is required when energized equipment is serviced or maintained, safety guards are removed or bypassed, a worker has to place any part of his or her body in the equipment's point of operation, or hazardous energy sources are present.

Lockout/tagout steps include:

- notify others that the equipment will be shut down,
- perform a controlled shutdown to power down the equipment,
- open all of the energy isolating devices identified on the equipment's specific LOTO procedure,
- lock and tag all energy isolating devices,
- dissipate or restrain stored or residual energy,
- verify that the equipment is completely de-energized by attempting to cycle it, and
- verify that the equipment is completely de-energized by testing for voltage with a voltmeter.

Proper LOTO labeling includes:

- name of the person placing the LOTO and the date placed,
- details regarding the shutdown procedure for specific equipment,
- a list of all of the energy sources and isolating devices, and
- labels indicating the nature and magnitude of stored potential or residual energy within the equipment.

The lock placed on equipment during servicing should be removed only by the person who placed it. The lockout devices, such as padlocks, shall be approved for LOTO applications. OSHA provides variations of LOTO that may be used depending on an approved energy control program. Safety protocols need to be followed when re-energizing equipment, including notifying others that the system is about to be energized.

### **3.2 PPE and Other Safety Equipment**

Service personnel must know what PPE is required for a specific task and wear it while completing the task. PPE includes fall protection, arc flash protection, fire-rated clothing, hot gloves, boots, and protective eyewear, among other items. PPE is designed to help minimize exposure to inherent system hazards. Identification of potential hazards is crucial to the process of selecting the appropriate PPE for the task at hand. All personnel working on or near PV systems should be trained to recognize hazards and choose the appropriate PPE to eliminate or reduce those hazards.

Rubber-insulating gloves, often referred to as "hot gloves," are the first line of defense against electric shock. They should always be worn with protective leather gloves over them and inspected before each use. Additionally, OSHA requires the gloves to be re-certified or replaced at regular intervals, beginning six months after they are placed in

service. Insulated hand tools provide an additional layer of shock protection.

As PV systems get larger and direct current (dc) operating voltages up to 1,000 volts (V) become increasingly common, arc flash requirements are a growing concern and it is more common to see arc flash warning labels on combiner boxes and disconnects. Unfortunately for maintenance personnel, many existing PV systems have been installed without labels warning of arc flash hazard. Service personnel need to be able to perform on-site evaluations to determine when a higher category of PPE is required to perform the work. Tasks such as performing thermal imaging on operating inverters with opened coverings or doors or verifying voltages in switchgear commonly require arc flash rated PPE.

Even when not required by statute or regulations, general industrial safety equipment such as hardhats, safety glasses, boots, fire-rated clothing, and safety vests is strongly recommended when working on construction sites or around live electrical equipment. The jobsite also must be equipped with appropriate fire extinguisher and first aid supplies and all personnel must have proper training in their use. Lastly, at least two qualified people trained in cardiopulmonary resuscitation (CPR) should be on site at all times.

### **3.3 Safe Operation of Electrical Disconnects**

Switching on or off an electrical contractor or disconnect is a process often taken for granted as safe but it can be one of the more dangerous tasks involved in maintaining a PV system. Workers must wear proper PPE when operating disconnects, and care should be taken to use the proper technique for throwing switches. Some of the switches used to control the dc circuits of PV systems are not rated for load-break operation. Non-load-break-rated switches, which must be labeled as non-load-break-rated, must never be opened while the system is operating. Before opening a dc switch that is not rated for load break, the system should be shut down by turning off the connected inverter.

The hinges of most disconnect switches are on the left side of the switch and the handles are on the right. A recommended safety protocol is to follow the left-hand rule, which involves standing to the right side of the switch and using the left hand to throw the switch. This ensures that the worker's body is not in front of the switch should an arc flash occur.

The proper technique for safely throwing an electrical disconnect includes:

- wear proper PPE,
- shut the system off at the inverter,
- stand to the right of the switch,
- grab the handle with the left hand,
- turn body and face away from the switch,
- close eyes,
- take a deep breath and hold it (to avoid breathing in flames if an arc flash occurs),
- throw (operate) the disconnect lever,
- use a properly rated voltmeter to confirm that no voltage is present on the disconnected circuit, and
- use LOTO methods to ensure the switch remains off.

### **3.4 PV-Specific Signage and Warnings**

Article 690 of the NEC (NFPA, 2011b) covers the requirements for PV-specific signage and warnings that must be present on every PV system. Additional signage may also be required by the local jurisdiction or utility. These placards and warnings need to be visible to those working on or near the systems and should never be covered or painted over.

Early PV systems often operated with maximum system voltages less than 50 Vdc. Today, 600 Vdc systems are common and 1,000 Vdc systems are allowed by code in commercial and large-scale installations. Qualified personnel must use properly rated equipment and be trained for servicing the higher voltage systems.

Particular care must be taken to observe and follow warning labels reading “DO NOT DISCONNECT UNDER LOAD” located on module connections, combiner boxes, disconnects, and some inverter switches not designed as a load-break switch. Failure to heed these warning labels can lead to instrument malfunction, arcing, fires, and personnel injuries.

Although it is impossible to compile a list of universally applicable safety guidelines, the authors suggest the following steps as crucial to safe work:

- Before operating the PV system, read all instructions for each product.
- All system components must be assumed to be energized with maximum dc voltages (up to 1,000 V) until personnel verify that the voltage has been removed.
- All enclosure doors should remain closed with latches tightened, except when they must be open for maintenance or testing.
- Only qualified personnel who meet all local and governmental code requirements for licensing and training for the installation of electrical power systems with alternating current (ac) and dc voltages up to 1,000 V (or 600 V, when applicable) should perform PV system servicing.
- To reduce the risk of electric shock, only qualified persons should perform servicing other than that specified in the installation instructions.
- In order to remove all sources of voltage from the inverter, the incoming power must be de-energized at the source. This may be done by opening the ac disconnect and the dc disconnect. Follow manufacturer guidelines for specifics of how to de-energize the inverter. In addition, allow a minimum of five minutes for the dc bus capacitors to discharge after disconnecting the power, always testing that voltage is reduced to touch-safe levels (30 Vdc) before working on the system.
- Always follow LOTO procedures.
- Always check for ground faults. If there is a ground fault, there may be a voltage potential between the inverter and ground. Further, check that the normally grounded pole is properly grounded and has not been energized by a fault.
- Do not work alone when servicing PV equipment. A team of two is required until the equipment is properly de-energized, locked-out, and tagged-out. Verify with a meter that the equipment is de-energized.
- Do not open a string (also known as a source circuit) combiner fuse holder without first confirming that there is no current flowing on the circuit.
- Do not disconnect (unplug) module leads, jumpers, or homerun wires under load.

## **4. ROUTINE SCHEDULED PREVENTIVE MAINTENANCE**

One of the most valuable techniques for identifying existing problems and preventing future problems is to walk the site and conduct a thorough visual and

hands-on inspection of the PV system components. These inspections should be conducted at regular intervals, and personnel should use checklists developed for these periodic maintenance activities to ensure that the inspections are thorough and complete.

#### **4.1 General Site Annual Inspection**

At least once a year, O&M personnel should conduct a general inspection of the PV installation site. During this inspection, technicians should:

- ensure roof penetrations are watertight, if applicable;
- ensure roof drainage is adequate, roof drains are not clogged, and confirm that there are no signs of water pooling in the vicinity of the array;
- check for vegetation growth or other new shade items such as a satellite dish;
- check for ground erosion near the footings of a ground mount system;
- confirm proper system signage is in place;
- confirm appropriate expansion joints are used where needed in long conduit runs;
- confirm electrical enclosures are only accessible to authorized personnel, are secured with padlocks or combination locks, and have restricted access signage;
- check for corrosion on the outside of enclosures and the racking system;
- check for cleanliness throughout the site there should be no debris in the inverter pad area or elsewhere;
- check for loose hanging wires in the array; and
- check for signs of animal infestation under the array.

#### **4.2 Detailed Visual Inspection**

The installation should be inspected regularly for issues that impact the physical integrity or performance of the PV system. A visual inspection should include the following actions:

- Inspect the inverter/electrical pad to make sure it does not show excessive cracking or signs of wear. The inverter should be bolted to the pad at all mounting points per the manufacturer installation requirements. Depending on the size, location, and accessibility of the system to unqualified personnel, the inverters, combiner boxes, and disconnect switches should require tools or have locks to prevent unauthorized access to the equipment.
- Look for warning placards including arc flash or PPE requirements for accessing equipment. Be sure to comply with all warning placards. If no placards are present, or if some placards are missing, make a note of it and install the missing placards during the maintenance visit. Consult the NEC and Underwriters Laboratories (UL) standards as well as the site host to determine signage requirements.
- Inspect PV modules for defects that can appear in the form of burn marks, discoloration, delamination, or broken glass.
- Check modules for excessive soiling from dirt buildup or animal droppings. (See [Array Washing Procedure](#) for proper procedures for cleaning an array.)
- Ensure that the module wiring is secure and not resting on the roof, hanging loose and exposed to potential damage, bent to an unapproved radius, or stretched across sharp or abrasive surfaces.
- Inspect racking system for defects including rust, corrosion, sagging, and missing or broken clips or bolts.
- If sprinklers are used to spray the array, check that the water is free of minerals (demineralized) as these minerals can cause gradual performance degradation.
- Inspect conduits for proper support, bushings, and expansion joints, where needed.

- In roof-mounted systems, check the integrity of the penetrations.
- In ground-mounted systems, look for signs of corrosion near the supports.
- Open combiner boxes and check for torque marks on the connections. Torque marks are made when lugs have been tightened to the proper torque value. Ideally they are applied during initial installation, but if not, the technician can mark the lug after torquing during a maintenance visit. A proper torque mark is made with a specialized torque marking pen. The mark is a straight line through the lug and the housing. Over time, if the line separates between the lug and the housing, it shows that the lug has moved and needs to be re-torqued. Look for debris inside the boxes and any evidence of damaging water intrusion. Look for discoloration on the terminals, boards, and fuse holders.
- Open the door to the disconnect(s) and look for signs of corrosion or damage. Check to make sure the cabinet penetrations are properly sealed and there is no evidence of water ingress. Check for torque marks on the terminals.
- Perform a visual inspection of the interior and exterior of the inverter. Look for signs of water, rodent, or dust intrusion into the inverter. Check for torque marks on the field terminations.
- If a weather station is present, ensure that the sensors are in the correct location and at the correct tilt and azimuth. A global horizontal irradiance sensor should be flat, and a plane of array irradiance sensor should be installed to the same pitch and orientation as the array. Irradiance sensors should be cleaned to remove dirt and bird droppings.

#### **4.3 Manufacturer-Specific Inverter Inspection**

Each inverter manufacturer will have specific requirements for inspection, testing, services, and documentation to meet its warranty obligations. Typical requirements for inverter inspections include:

- Record and validate all voltages and production values from the human-machine interface (HMI) display.
- Record last logged system error.
- Clean filters.
- Clean the inside of the cabinet.
- Test fans for proper operation.
- Check fuses.
- Check torque on terminations.
- Check gasket seal.
- Confirm warning labels are in place.
- Look for discoloration from excessive heat buildup.
- Check integrity of lightning arrestors.
- Check continuity of system ground and equipment grounding.
- Check mechanical connection of the inverter to the wall or ground.
- Check internal disconnect operation.
- Verify that current software is installed.
- Contact installer and/or manufacturer about any issues found.
- Document findings for all work performed.

#### **4.4 Manufacturer-Specific Tracker Inspection**

Tracker manufacturers will have specific requirements for inspections, testing, service, and documentation to meet their warranty obligations. Typical maintenance or startup requirements for tracker systems include:

- Lubricate tracker by inserting grease with grease gun into appropriate grease caps per manufacturer maintenance recommendation.
- Check voltages inside the controller box.
- Use a digital level to check the calibration and positioning of the inclinometers.
- Check array for signs of parts hitting or rubbing other parts.
- Remove vegetation that is near the drive shaft or moving components.
- Check wind-stow operation.

Use appropriate (volt, ohm, dc clamp-on) meters to test:

- continuity of the equipment grounding at the inverter, combiner boxes, and disconnects;
- continuity of all system fuses at the combiner boxes, disconnects, and inside the inverter(s);
- open-circuit voltage (Voc) of all strings with the inverter off; and maximum power current (Imp) of all strings with the inverter on and at specified or recorded levels of power.

Additional testing (used when problems are identified or required by contract terms) may include:

- thermal images of combiner boxes (opened and closed), disconnects, inverters (external and internal at a specified operating point for a specified period of time), and modules;
- short circuit (Isc) testing of strings;
- current-voltage (IV) curve testing of strings;
- insulation resistance tests (also known as “megger” tests) of conductors at specified voltage; and
- comparison of a weather-corrected performance calculation of expected output to actual output of the system.

#### **4.5 Manufacturer-Specific Data Acquisition System Inspection**

Data acquisition system (DAS) manufacturers will have specific requirements for inspections, testing, service, and documentation to meet their warranty obligations.

Typical maintenance or startup requirements for DASs include:

- taking voltage readings of power supplies,
- validating current transducer readings by comparing to calibrated equipment, and
- validating sensor reading by comparing to calibrated equipment.

To confirm proper functionality of the DAS, the values measured by the DAS must be verified against values from devices with traceable calibration records. Comparing the irradiance, temperature, and power measurements recorded by the DAS to values obtained from calibrated instruments will help identify sensor calibration issues that could result in the DAS data being incorrect.

The PV industry as a whole is getting better at DAS installation and documentation, but it is still typical for DAS plans to be omitted or insufficiently detailed. As a result of such an omission, plan checkers often do not check for errors in the DAS design and inspectors have nothing to compare the as-built with for compliance. If the DAS will be tied into the building information technology system, O&M personnel should

be aware that building networking upgrades or routine maintenance can cause connectivity issues.

## **5. GENERAL ISOLATION PROCEDURES**

### **5.1 Energized Components**

Some testing and maintenance activities may require the system to be energized while workers are working on or near the equipment—string current testing is one example. Another common testing practice discussed in Megohmmeter Testing (megger testing) is to use an insulation resistance meter to induce voltage to wiring or other components in an effort to identify signs of damage to insulation or resistance/leakage from other sources such as loose connections.

OSHA provides guidance for what must be done in order to work safely on energized systems:

- Only qualified employees can work on electric circuits or equipment that has not been de-energized using LOTO procedures.
- Qualified employees must be able to work safely on energized circuits.
- The qualified employee must be familiar with the proper use of special precautionary techniques, PPE, insulating and shielding materials, and insulated tools.
- Employees working in areas where there are potential electrical hazards must be provided with and use electrical protective equipment that is appropriate for the specific parts of the body to be protected and for the work to be performed.

### **5.2 Inverter Pad Equipment**

Use the following procedures for disconnecting a single inverter from the grid:

- If applicable, follow the inverter manufacturer guidelines for a controlled shutdown using the HMI keypad to navigate and select a shutdown.
- If the inverter has an on/off switch, turn it to off.
- Turn the ac disconnect switch on the inverter off.
- Turn the dc disconnect switch on the inverter off.
- Turn any remaining external disconnect switches connected to the inverter off.
- Install lockout devices on all disconnects, locking them in the open or off position.
- Repeat for all inverters and switches to completely isolate the entire PV system from the grid and the inverters from the PV power source.

### **5.3 Transformer Isolation**

Use the following procedures for transformer shutdown:

- For inverters connected to the transformer, turn the on/off switch to off.
- Turn the ac disconnect off for the inverters connected to the transformer.
- Turn the dc disconnect off for the inverters connected to the transformer.
- Install lockout devices on the disconnects.
- Turn off the transformer switch, which is either a dedicated stand-alone switch or is located in the switchgear.
- Install a lockout device on the transformer switch.
- Repeat for all transformers to completely isolate them from the switchgear.

## **6. FAILURE RESPONSE**

### **6.1 Emergency Shutdown**

In an emergency situation:

- If the inverters have Emergency Stop buttons, push them in on each inverter.
- If the inverter has an on/off switch, turn it to the off position (this may require a key). Each inverter should be manually turned to the off position. This will immediately open the internal ac and dc contactors (if present) inside the inverter.

Note that some inverters do not have an on/off switch or an Emergency Stop button. For these inverters, it will be necessary to turn the systems off using the disconnect switches attached to or located near the inverters. Do not open switches that are specifically labeled “Do not disconnect under load” until a load-break switch has been opened and current flow is stopped. Generally, the first available upstream load-break ac switch or circuit breaker is safer to operate first (before the dc switch), because the inverter instantly shuts down the transistor bridge when ac voltage is removed. Once the system is off, the remaining switches can be opened and the system can be locked out until the fault condition is repaired or it is safe to turn it back on.

### **6.2 Isolation Procedure Inverter Pad Equipment**

To isolate the inverter pad safely:

- Shut the inverters off through a controlled shutdown.
- Turn off all dc and ac disconnect that feed the pad. Follow the procedure in the LOTO section for opening electrical disconnects.
- Use LOTO procedures to ensure the system remains off.
- Always wear appropriate PPE and test for voltages with a properly rated meter to confirm the system is completely isolated.

### **6.3 Isolation Procedure Field Combiner Box**

To isolate field combiner boxes:

- Turn off the inverters as described above.
- Operate the switch of the combiner (if applicable) by turning the handle to the off position.
- Use a dc clamp on the meter to confirm there is no current passing through the ungrounded conductors in the combiner box, and then open all of the fuses.
- If further isolation of the box is needed, use the string diagrams to locate the homeruns (end connectors of the PV strings).
- Use a clamp-on dc current meter to confirm that the homerun does not have any current passing through it, and then disconnect the string by opening the homerun positive and negative connectors and putting caps on the source circuit connectors.
- Go back to the combiner box and use a voltmeter to confirm that each string has been successfully disconnected.

### **6.4 Isolation Procedure Modules and String Wiring**

After turning off the inverter, switches, and combiner boxes and isolating the combiner boxes from the array, disconnect individual modules from the string:

- Before disconnecting any string, use a dc clamp-on meter to confirm there is no current passing through the string.

- Use the appropriate connector unlocking tool to disengage the module connector.
- Repeat for each module to be isolated from the system.
- If modules are removed from a system, even temporarily, technicians must ensure that the equipment grounding system remains intact for the remaining modules.

## **7. INVERTER TROUBLESHOOTING AND SERVICE**

There is an understandable focus on maximizing ROI and system production. System uptime and availability is a key objective of O&M. Inverters that are offline can have a dramatic negative impact on the ROI of a PV system. Inverter failure rates are important to ROI, but even more important than how often an inverter goes offline is how quickly it can be placed back into service. The type of inverter fault often dictates how quickly it can be placed back into service. Inverters with known failure modes need a failure response procedure. This may include stocking critical parts that have long supply lead times so that the system is not left offline because of a lack of spare parts.

### **7.1 Inverter Troubleshooting**

When an inverter goes offline, technicians must determine why and correct the error as quickly as possible. They can check the HMI for reported errors, and then follow the actions noted in the table below.

### **7.2 Common Reported Inverter Errors**

Inverter Error	Action
Dc undervoltage	Steps to diagnosing underperforming systems
Dc overvoltage	Voc string testing
Dc ground fault	Ground fault detection procedure
Gating fault	Check connections Contact manufacturer
Ac undervoltage	Confirm all breakers are on Check ac voltage with voltmeter If within range, perform a manual restart If outside of
Ac overvoltage	Check ac voltage with voltmeter If within range, perform a manual restart If outside of range, contact utility
Low power	System is likely just shutting down because of lack of sun; if it is sunny, perform steps to diagnose underperforming systems
Over temperature fan not operating	Check power supply to fan if good, replace fan; if bad, replace power supply
Over temperature fan is operating	Check to confirm sensor readings if bad, replace sensor; if good, investigate further
Over temperature fan is operating, sensors are accurate	Check intake and exhaust filters for excessive buildup, and clean or replace if necessary
Software fault	Contact manufacturer

Some inverter faults will clear automatically when the fault condition returns to

normal, but some fault conditions require a manual reset of the inverter. The ground fault fuse and even ac fuses can be non-standard items that are difficult to purchase. Keep replacements on hand, especially if there are multiple inverters of the same size on site or in the portfolio. Having qualified technicians available and properly equipped with common replacement parts helps maximize system uptime.

### **7.3 Inverter Service Procedures**

Some inverter service actions require that the system be shut down for safe inspection. Always begin with an examination of the equipment, and further inspect subassemblies, wiring harnesses, contacts, and major components.

The following sample inverter service checklist applies to larger inverters (not residential scale) and is not intended to be complete for all models from all manufacturers:

- Check insulated gate bi-polar transistors and inverter boards for discoloration. Use inspection mirror if necessary.
- Check input dc and output ac capacitors for signs of damage from overheating.
- Record all voltage and current readings from the front display panel.
- Check appearance/cleanliness of the cabinet, ventilation system, and insulated surfaces.
- Check for corrosion/overheating on terminals and cables.
- Torque terminals, connectors, and bolts as needed.
- Record ambient weather conditions, including the temperature and whether the day is cloudy or sunny.
- Check the appearance of both the ac and dc surge suppressors for damage or burn marks.
- Check the operation of all safety devices (emergency stop devices, door switches, ground fault detector interrupter).
- Inspect (clean or replace) air filter elements.
- Correct any detected deficiencies.
- Complete maintenance schedule card.
- Complete written inspection report.
- If manufacturer-trained personnel are available on-site, install and perform any recommended engineering field modifications, including software upgrades.

## **8. DIAGNOSING AND TESTING FOR LOW POWER PRODUCTION**

Low power production also impacts ROI, and O&M personnel need effective strategies for identifying and correcting problems quickly. System operators or owners may become aware of a PV installation's underperformance through one of the following means:

- a predefined DAS alert, which may be weather-related, a result of comparison with other systems in the portfolio, or a result of comparison with other monitored parts of the system at a site with multiple inverters;
- a manual review of the DAS data through online portal that indicates performance anomalies;
- a comparison of present performance with performance test results from previous maintenance visits; and
- customer or external entity reports of a potential problem, often because of an unexpected increase in a monthly bill.

## 8.1 Diagnostic Overview

Once the underperformance is confirmed, personnel must determine what is causing it.

Steps to diagnosing power production deficiencies include:

- During routine maintenance and when diagnosing an underperforming system, the first and most important components to check are the fuses. Fuses generally must be removed from their holders to determine whether they have blown.
- Perform a system performance data review using the DAS or a program such as the PVWatts calculator (NREL, 2012) to calculate the expected system output based on weather conditions and system size to compare actual to modeled systems production.
- Dispatch a field technician to the site to do the following:
  - Check that on-site performance meters have similar values. Often systems will have revenue grade performance monitoring that can be compared against the inverter display totals.
  - If there is a difference in the values, then ideally the technician can log into the DAS system (when available) to investigate.
- A phase that has a different output than the others could be the result of a bad current transformer (CT) or a blown fuse in the CT circuit (i.e., an instrumentation problem).
  - If there is no difference in recorded values, then use the inverter operator display/interface (if applicable) to identify the inverter error log. See inverter diagnostics for errors that may have caused the inverter to perform at less than 100% power.
  - Verify that the array maximum power point voltage is in the maximum power point tracking window of the inverter, using an IV curve tracer on a sample string or group of strings. Modules will degrade over time and an array that begins service at the lower end of the inverter maximum power voltage window may degrade until its maximum power voltage no longer falls within this range, further compounding the effects of module degradation.
  - Look for external causes of the production drop, such as unexpected shade on the array. Vegetation growth is the most common form of shading, but it is not unusual to find a satellite dish or other object shading the array that was not present when the system was built. Take photographs of the installation during commissioning and keep a visual record of any noticeable differences during maintenance visits.
  - Perform general system checks as necessary to identify problems:
- Check all fuses at the inverter and work out to the combiner boxes.
- Perform Voc string testing.
- Perform Imp string testing.
- Validate weather sensors.
- Look for soiling. If soiling might be the problem, test an individual string (Voc, Imp, IV curve) and then clean the string and retest.
- Perform IV curve tracing.
- Take infrared (IR) images of the PV cells.

## **8.2 Diagnostic Testing**

O&M personnel can use a number of diagnostic procedures to determine the cause(s) of power deficiencies in a PV installation. The following sections describe these tests in detail.

## **8.3 Infrared (IR) Image Procedure**

This procedure describes how to properly perform field diagnostics of a PV installation using an IR camera to detect abnormal heat signatures. Topics include correct camera settings and proper conditions for field inspection.

## **8.4 Test conditions**

- IR imaging should be completed with the system operating at peak levels
- if possible.
- Do not open or work in electrical boxes, particularly those with NEMA 4 rating, during rainy or wet conditions.

## **8.5 Tools include:**

- IR Camera, such as Fluke Ti10, Fluke Ti32, FLIR i40, or FLIR i7; and
- clamp-on ammeter.

## **8.6 Safety considerations.**

- Ensure all OSHA and environmental health and safety requirements are met,
- especially if working on angled roofs and/or at heights greater than six feet.
- Safety precautions should also be taken when working near active high voltage systems or near surfaces that may be very hot to the touch.
- Contact local health, security, safety, and environment personnel for questions
- and access to pertinent documentation

## **8.7 IR imaging procedure.**

- Before starting the IR scan, verify that the PV array is operating, because temperature differences in modules are not apparent when the system is not operational.
- Check inverter display for instantaneous kilowatt output.
- Check current on each string in combiner box to ensure that it is operational.
- If the inverter or any of the strings are not operational, these must be corrected before the test can be conducted.

## **8.8 IR camera settings.**

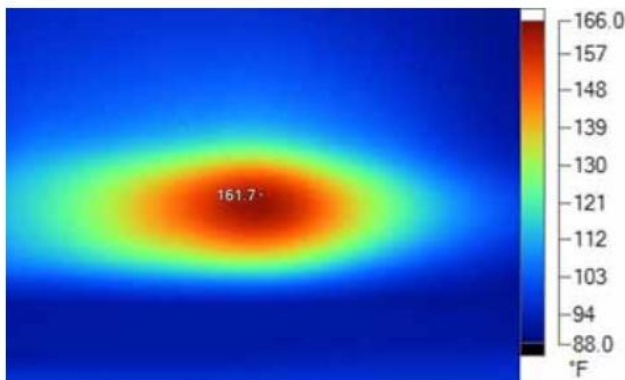
- Set the IR camera to “auto-scaling” rather than manual scaling. This will allow for automatic adjustment of the temperature scale.
- Set emissivity value to 0.95 (usually the camera default). The IR camera does not capture shiny surfaces such as polished metals well due to their low emissivity value. However, for most active components on a solar module such as cells, J-Box, and cables, a value of 0.95 will be sufficient.
- Set temperature units to Celsius.
- Set color palette to Iron or Rainbow. “A thermal imager interprets IR radiated or reflected heat by assigning a visible graduated color or gray scale to a radiated portrait of the scene. The color palette displays hot spots as white with diminishing temperatures through red-orange-yellow-green-blue-indigo- violet to black being cold” (Fluke Corporation, 2006, 2008).

### 8.9 IR inspection.

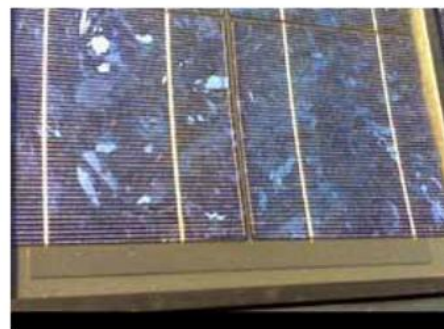
- When sunlight is present and camera settings are properly set, point the lens at the object of interest. In the case of solar modules in operation, looking through the glass onto the active cells is the most common inspection technique.
- Ensure that the picture is focused, either manually or automatically. For best results, position the camera as close to the module as possible without shading it or creating a reflection in the glass surface. If possible, the distance between the camera and the surface to be measured should not exceed three meters or 10 feet. This will depend on the camera's minimum focal distance and other specifications. Some temperature differences will not be picked up if the camera is too far away from the module.
- For best results, position the camera as perpendicular as possible to the object being measured. Hot spots will be easier to see if the image is taken perpendicular to the module surface. Image quality will degrade at camera angles other than normal (i.e. perpendicular) incidence.
- Care should be taken to avoid shading any part of the module while capturing images.
- Record module serial number, time, date, picture number, and module location in the array for all issues.

### 8.10 Sample Images

*Junction boxes on back surface of a PV module*

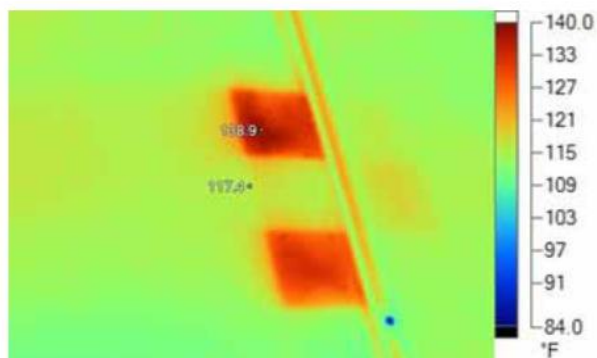


IR Image



Visible light image

*Cells in a module*



IR Image



Visible Light Image

### *Megohmmeter Testing*

Megohmmeter or “megger” testing is a valuable way to identify weakened conductor insulation and loose wiring connections. These tests are often used in system

acceptance and commissioning procedures but not often used in general maintenance unless a thorough troubleshooting of a fault condition is needed. The insulation resistance tester (IRT) applies a voltage to the circuit under test and measures return current to determine the insulation resistance and integrity. IRTs have various test voltage settings, such as 50 V, 100 V, 250 V, 500 V, and 1,000 V. Generally, the higher voltage settings are better for detecting high impedance shorts in the wiring than lower voltage settings. However, some newer low voltage equipment has sophisticated filtering that enables effective measurements even on circuits with PV modules. All 600 V-rated wire and PV modules should be capable of being tested at 1,000 Vdc, because they are factory proof tested at twice the maximum rated voltage plus 1,000 V—this adds up to 2,200 V for 600 V cable and PV modules. This test is short-term and will not damage the wire or module insulation.

To test specific products, including strings of modules, it is best to confirm that the testing (high voltage) will not void the warranties of those materials. It is best to get written permission for testing procedures from the module manufacturer if they do not already have approved megohmmeter testing guidelines. Some manufacturers explicitly disallow megohmmeter testing on their modules. Although it is true that some products may not allow this testing, the most common location of ground faults in PV systems is in the module wiring and modules.

Testing using the 500 Vdc setting may be appropriate for some modules. Lower voltages are often necessary when the system includes surge protection devices within the combiner boxes. Insulation testers are now available with 50 Vdc settings that will not damage the surge protectors. If these are used it is important to ensure that they have filtering capable of compensating for the array capacitance. The added benefit of a low voltage insulation test is that it can detect problems with surge protectors. Leaking surge protectors are a common fault of older PV systems.

#### *Test conditions*

- Do not open or work in electrical boxes, particularly those with NEMA 4 rating, in wet conditions.
- Tools include:
  - IRT megohmmeter;
  - PPE rated for the appropriate voltages;
  - screwdriver or combiner box key, if applicable;
  - dc clamp-on meter;
  - dc voltmeter;
  - electrical tape;
  - system drawings string wiring diagram;
  - warning signs: “High Voltage Testing in progress Stay clear of photovoltaic array!”; and
- recording device (pen and paper, laptop or tablet preferred).

#### *Safety considerations include:*

- shock hazard, live voltages present;
- fall hazard, combiner boxes are often elevated;
- need for proper PPE for electrical voltage testing;
- recognition that normally de-energized circuits may be energized in fault conditions; and

- requirement for two qualified people trained in CPR.

*IRT testing procedure:*

- Turn system off at the inverter.
- Post “High Voltage,” Testing in progress,” “Stay clear of photovoltaic array!”
- signs around all entry points to array.
- Use LOTO procedures.
- Record test conditions including ambient temperature and irradiance.
- Open disconnect switch on combiner box, if applicable. If there is no switch at the combiner box, open the applicable disconnect or fuse at the inverter to isolate the combiner box circuit.
- Isolate the output circuit grounded conductor (negative in a negative grounded system, positive in a positive grounded system) by removing the cable from its termination.
- Remove any surge protection devices from circuits being tested (if testing at more than 50 Vdc).
- Visually inspect box for signs of damage, including:
  - heat discoloration,
  - corrosion,
  - water intrusion, and
  - conductors rubbing against metal in enclosure or other insulation damage.
- Use dc current meter to confirm there is no current present in the
- combiner box.
- Open all fuse holders.
- Use ohmmeter to verify continuity of the box enclosure to ground. If enclosure
- is not metal, verify ground wire connection to ground.
- Test  $V_{oc}$  of all strings to confirm proper polarity and voltage of each string.

**8.10 FOR POSITIVELY GROUNDED SYSTEMS:**

First, test all strings in the box simultaneously:

- Set megohmmeter on a sturdy surface. Attach red lead to red terminal on
- tester. Attach black lead to black terminal on tester.
- Attach the red (positive) lead from megohmmeter to the ground busbar in the combiner using an alligator clip. Attach black (negative) lead from megohmmeter to the positive busbar (unfused side).

If low impedance is detected at the box level, test the individual strings:

- Remove positive string conductors one at a time from the grounded conductor (positive) busbar, capping each with a wire nut before moving to the next. Make sure there is no exposed copper once the wire nut is tight.
- Set megohmmeter on a sturdy surface. Attach red lead to red terminal on
- tester. Attach black lead to black terminal on tester.
- Attach the red (positive) lead from megohmmeter to the ground busbar in the combiner using an alligator clip. Attach black (negative) lead from megohmmeter to the positive lead of the string.

**8.11 FOR NEGATIVELY GROUNDED SYSTEMS:**

First, test all strings in the box simultaneously:

- Set megohmmeter on a sturdy surface. Attach red lead to red terminal on
- tester. Attach black lead to black terminal on tester.
- Attach the black (negative) lead from megohmmeter to the ground busbar in the

combiner using an alligator clip. Attach the red (positive) lead from megohmmeter to the negative busbar (unfused side).

If low impedance is detected at the box level, test the individual strings:

- Remove negative string conductors one at a time from the grounded conductor busbar, capping each with a wire nut before moving to the next. Make sure there is no exposed copper once the wire nut is tight.
- Set megohmmeter on a sturdy surface. Attach red lead to red terminal on tester. Attach black lead to black terminal on tester.
- Attach the black (negative) lead from megohmmeter to the ground busbar in the combiner using an alligator clip. Attach red (positive) lead from megohmmeter to the negative lead of the string.

#### **8.12 FOR UNGROUNDED SYSTEMS:**

For ungrounded systems, note there should be two pole switches to completely isolate the positive and negative combiner circuits from the inverter and other combiner boxes, so there should be no need to remove an output circuit cable from its terminal.

First, test all strings in the box simultaneously:

- Open the positive fuse holders only in the combiner box, leaving the negative fuse holders closed in.
- Set megohmmeter on a sturdy surface. Attach red lead to red terminal on tester. Attach black lead to black terminal on tester.
- Attach the black (negative) lead from megohmmeter to the ground busbar in the combiner using an alligator clip. Attach the red (positive) lead from megohmmeter to the negative busbar.

If low impedance is detected at the box level, test the individual strings:

- Open all of the positive and negative fuse holders. The string conductors do not need to be removed from the fuse holders.
- Set megohmmeter on a sturdy surface. Attach red lead to red terminal on tester. Attach black lead to black terminal on tester.
- Attach the black (negative) lead from megohmmeter to the ground busbar in the combiner using an alligator clip. Attach red (positive) lead from megohmmeter to the negative lead of the string, using the array-side screw terminal of the fuse holder.
- After positive leads are tested using the procedure below, repeat the test on the negative leads of the string using the array-side screw terminal of the fuse holder.
- Set meter to the appropriate voltage setting.
- Press and hold the “Test” button for a specific and consistent time period—at least 15 seconds.
- Watch the display of the meter closely during the 15 second tests and look for fluctuations in the readings.
- Record the result after the 15 second interval. Insulation resistance measurements will vary based on system age, moisture, temperature, and the size of the string under test. Because absolute numbers vary based on these and other conditions, typically a string conductor with a value of greater than one to three megaohms is considered passing (Mync & Berdner, 2009). Box level measurements can be lower, as low as 500 kilohms. Because of the variable conditions stated above, it is important to look for relative differences in the measurements of different boxes.
- Repeat test until all strings are tested.

- If a string fails the test, isolate the conductors from the array and test again.
- Replace or repair all wiring in any failed strings.
- Record all results for future comparison.

### **8.13 Fuse Checks**

Fuses blow for a reason. Whenever a blown fuse is found, investigate why the fuse blew. When replacing fuses, it is essential to source the appropriate size, type, and rating. Do not assume that the fuse being replaced was the correct size, type, and rating, because an incorrect rating or size could be the reason the fuse blew. It may be necessary to consult the product manual to ensure the correct fuse is sourced. It is common to come across operating systems with incorrect fuses in place.

#### *Test conditions:*

- Fuses can be checked under any test conditions.
- Do not open or work in electrical boxes, particularly those with NEMA 4 rating, in wet conditions.

#### *Tools include:*

- ohmmeter;
- PPE;
- screwdriver or combiner box key, if applicable;
- fuse puller, if applicable; and
- recording device (pen and paper, laptop or tablet preferred).

#### *Safety considerations:*

- Fuses should never be replaced or tested while the circuit is energized. Shut the system down prior to servicing fuses.
- Wear proper PPE for electrical voltage testing, at least until no voltage has been verified and the source has been locked out, if applicable.

#### *Fuse testing procedure:*

- Confirm system is de-energized with a voltmeter.
- Use LOTO procedures.
- Use an ohmmeter to test the continuity of the fuse. It may be possible to get voltage through a fuse that has not completely blown but is about to blow. For this reason, having voltage only on the load side of the fuse is not enough.
- Set ohmmeter on a sturdy surface.
- Remove the fuse to be tested from the fuse holder unless it is clear that no alternative continuity paths can exist that would provide a false reading.
- Use meter and test the fuse by placing a lead on each end of the fuse and listening for the meter to beep confirming continuity.
- If the beep continuity reading is not constant while still holding the leads on each end of the fuse, then look at the ohm settings for a measurement of the resistance. Make sure your fingers are not touching each end of the fuse as this will give a resistance reading for an open fuse that can be confusing.
- Look at the fuse and confirm the size, type, and rating of the fuse.
- If the fuse fails the test or is not the properly rated size or type, replace the fuse with the correct fuse.
- Always test replacement fuses before installing to confirm the fuse was good when it was placed in service.

### **8.14 Best practices.**

While testing the voltages with the system off and the fuses open, prep the box for current testing. Cut zip ties if needed and make sure the conductors are tight in their terminals and will not come out when the current clamp is placed around them in the next phase of testing.

Test with a two-person team so one can keep the safety equipment on and take readings while the other records the readings. This will allow for efficient testing, because the person taking the readings can enter them directly into a form. In addition, there is the safety advantage of having two people present when working on live equipment.

#### *DC System $V_{oc}$ Checks.*

DC voltage checks are done with the system off, but depending on the system size voltages of up to 1,000 Vdc may be present.

#### *Test conditions:*

- Ideally, test in stable sunlight of more than 750 watts per square meter (W/m<sup>2</sup>). However, stable conditions more than 200 W/m<sup>2</sup> still allow for simple comparisons among strings.
- Do not open or work in electrical boxes, particularly those with NEMA 4 rating, in wet conditions.
- Perform testing at the combiner boxes.

#### *Tools include:*

- dc voltmeter;
- PPE;
- irradiance meter;
- temperature sensor;
- screwdriver or combiner box key, if applicable; and
- recording device (pen and paper, laptop or tablet preferred).

#### *Safety considerations include:*

- shock hazard, live voltages present;
- fall hazard, combiner boxes are often elevated;
- proper PPE for electrical voltage testing;
- recognition that normally de-energized circuits may be energized in fault conditions; and
- requirement for two qualified people trained in CPR.

#### *Voltage testing procedure:*

- Turn system off at the inverter.
- Use LOTO procedures.
- Record test conditions including ambient temperature and irradiance.
- Open disconnect switch on combiner box, if applicable.
- Visually inspect box for signs of damage, including:
  - heat discoloration,
  - corrosion,
  - water intrusion, and
  - conductors rubbing against metal in enclosure or other insulation damage.

- Open all fuse holders.
- Attach red lead to red terminal on tester. Attach black lead to black terminal on tester.
- Use ohmmeter to verify continuity of the box enclosure to ground. If enclosure is not metal, verify ground wire connection to ground.
- Use dc clamp-on ammeter to test for current in the equipment grounding conductor. If current is present, stop this procedure and proceed to the Ground Fault Troubleshooting procedure.
- Use voltmeter to test equipment grounding conductor to ground:
  - If voltage is present, find source of problem before placing combiner box back into service.
  - Test ungrounded conductors one at a time by removing them from the bussing. Wear PPE and use insulated tools to remove ungrounded conductors under a fault condition.
- Ideally, use an alligator clip meter cable for the black lead, connect to ground.
- Take the red lead and individually test from the line side of the open fuse holder for the ungrounded conductor.
- Record results.
  - Note voltage and polarity of each string, and if polarity is incorrect, find the source of problem before placing back into service.
  - If reverse polarity is observed, do not just switch it without further investigation to identify the problem. Re-identify and properly label conductors if a switch is made. A change to the as-built plans may also be necessary.
  - All voltages should be within 10% of each other. If one string is the equivalent of the  $V_{oc}$  of one module (roughly 30-40 V depending on the module) less than the average and one string is 30-40 V more than the average, it is a good indication that the stringing is incorrect for both strings.
  - Given the same example of 40  $V_{oc}$ , if one string is 10-20 V less, then there may be an issue with one of the modules, and further investigation may be necessary (such as performing IV curve tracing).
  - If  $I_{mp}$  testing is going to be carried out in the same combiner box, it is best to prep the box for the  $I_{mp}$  testing.
  - Ensure all terminations are properly torqued.
  - Pull on conductors to ensure a large enough loop for the current meter to attach to. If necessary, cut zip ties.
- Close fuse holders.
- Close disconnect.

#### *DC System $I_{mp}$ Checks*

The dc  $I_{mp}$  tests are completed with the system running. Full operating voltages and current are present in the combiner boxes.

#### *Test conditions:*

- Ideally, test in full, stable sunlight. Usually, a minimum stable irradiance of 500 W/m<sup>2</sup> will allow for accurate comparisons among strings.
- Do not open or work in electrical boxes, particularly those with NEMA 4 rating, in wet conditions.
- Do the testing at the combiner boxes. The ambient test conditions should be

recorded for each combiner box. This includes the ambient temperature and plane of array irradiance. If a calibrated weather station is installed, a time stamp can be used to pull the data from the weather station or handheld tools can be used to record the real time values.

*Tools include:*

- dc clamp meter;
- PPE;
- irradiance meter;
- temperature sensor;
- wrench or additional combiner box handle;
- screwdriver or combiner box key, if applicable; and
- recording device (pen and paper, laptop or tablet preferred)

*Safety considerations include:*

- shock hazard, live voltages and current present;
- fall hazard, combiner boxes are often elevated;
- proper PPE for electrical current testing; and
- requirement for two qualified people trained in CPR.

*I<sub>mp</sub> testing procedure:*

- With system operating, open dc combiner box.
- It may be necessary to use a wrench or other handle type tool to close the combiner box switch (if the system is so equipped) with the door open. Technicians should wear proper PPE.
- Box should be prepped in advance during the voltage testing process.
- Fuse holders are not meant to be opened under load.
- The dc combiner boxes may not be designed to be turned off under load—look for warning labels.
- With a two-person team, an electrician wearing the proper PPE places a dc clamp-on meter around each individual string, calling out the numbers to the helper who records the data.
- Close the combiner box lid.
- If the combiner box lid cannot be closed with the switch closed, turn the inverter off and then open the switch rather than shutting off the switch with the door open. This is usually more efficiently done after all combiner boxes are tested rather than individually.
- Compare the I<sub>mp</sub> results of strings with identical pitch and orientation and similar test conditions to look for low-performing strings.
- Low performing strings can be further diagnosed using the steps for diagnosing production issues in the [Diagnostic Overview](#) section.

### **8.15 Grounding System Integrity Checks**

It is important to verify that the equipment ground is properly installed on all exposed non-current carrying metal parts. That way, the removal of a single piece of equipment—during module replacement, for example—does not impact the integrity of the bonding of the remaining equipment. If removal of any component results in a break in the bond connection, a jumper of suitable ampacity must be used as a temporary connection.

*Test conditions:*

- Tests can be performed in any weather condition.
- Do not open or work in electrical boxes, particularly those with NEMA 4 rating, in wet conditions.

*Tools include:*

- ohmmeter;
- screwdrivers; and
- keys to open enclosures, if applicable.

*Safety considerations include:*

- This test presents a fall hazard, because some of the system grounding equipment may be located higher than six feet and will require fall protection per OSHA 1926 Subpart M.

*Procedure:*

- Set ohmmeter to the continuity setting.
- Touch one lead to a metal surface or ground wire.
- Touch the other lead to a nearby metal surface or ground wire.
- Confirm continuity between the two surfaces by listening for the beep when the leads touch the surfaces at the same time.
- Repeat this process randomly throughout the array and at every combiner box, disconnect, and inverter.

### **8.16 DAS Check.**

DAS checks are used to validate the existing systems. If any component is not up to specs, it may be quicker and cheaper to replace it with a new component than to attempt alter settings. In some cases, the cheapest and best option may be to establish a policy of replacing equipment such as irradiance sensors at defined intervals rather than spend the time validating the data and then replacing when out of calibration.

*Test conditions*

- Ideally, test in full, stable sunlight.
- Do not open or work in electrical boxes, particularly those with NEMA 4 rating, in wet conditions.
- Do the testing at the equipment involved, which can be installed throughout the system in combiner boxes, switchgear, transformers, and inverters in the array as well as in separate dedicated DAS enclosures.
- Tools include:
  - ac/dc voltmeter;
  - ohmmeter;
  - laptop;
  - computer software (DAS/manufacture-specific);
  - computer cables (Ethernet, Crossover, RS232 to USB, RS485 to USB);
  - PPE;
  - irradiance meter;
  - temperature sensor;
  - level;
  - inclinometer;

- compass;
- screwdrivers/sockets; and
- equipment keys, if applicable.
- Safety considerations include:
  - shock hazard, live voltages present;
  - fall hazard combiner boxes and meteorological stations are often installed at heights of more than six feet and will require fall protection per OSHA requirements;
  - proper PPE for electrical voltage testing;
  - normally de-energized circuits may be energized in fault conditions; and
  - requirement for two qualified people trained in CPR.

#### *Testing procedure*

- Global horizontal irradiance:
  - Ensure location is not shaded.
  - Use level to make sure it is level.
  - Clean with a cloth and mild soap solution if necessary.
  - Log in to DAS program.
  - Place cleaned and recently calibrated handheld sensor in same pitch and orientation.
  - Compare results.
  - If outside of acceptable range, replace sensor, noting serial number of the new sensor for as-built updates.
- Plane of array irradiance:
  - Ensure location is not shaded.
  - Use inclinometer and compass to ensure it is in the same pitch and orientation as the array.
  - Clean with a cloth and mild soap solution if necessary.
  - Log in to DAS program.
  - Place cleaned and recently calibrated handheld sensor in same pitch and orientation.
  - Compare results.
  - If outside of acceptable range, replace sensor, noting the serial number of the new sensor for as-built updates.
- Ambient temperature sensor:
  - Log in to DAS program.
  - Take reading from handheld temperature sensor.
  - Compare results.
  - If outside of acceptable range, replace sensor, noting the serial number of the new sensor for as-built updates.
- Back of module temperature sensor:
  - Ensure sensor is correctly adhered to the back of a module in the middle of a cell in the middle of the module.
  - Log in to DAS program.
  - Take reading from handheld temperature sensor.
  - Compare results.
  - If outside of acceptable range, replace sensor, noting the serial number of new sensors for as-built updates.
- Rather than risk damaging the module, leave the sensor in place and install the new sensor in the middle of the next closest cell.

- Anemometer:
  - Log in to DAS Program.
  - Hold the anemometer and confirm it is reading 0 MPH.
  - Turn to confirm it is moving.
  - If further testing is needed, use a handheld anemometer and compare the results at a consistent windspeed greater than three meters per second.
  - If outside of acceptable range, replace sensor, noting the serial number of new sensors for as-built updates.
- Current transducers:
  - Log in to DAS Program.
  - Basic test is to compare the current readings to the inverter display current readings.
  - Revenue grade validating involves using a calibrated current meter and placing it around the same conductors with the system running.
- Proper PPE must be worn when testing live circuits.
  - Compare results.
  - If outside of acceptable range, replace sensor, noting the serial number of new sensors for as-built updates.
- Voltage reference:
  - Log in to DAS program.
  - Check fuses with ohmmeter.
  - Use calibrated voltmeter to test circuits.
- Proper PPE must be worn when testing live circuits.
  - Compare results.
  - If any difference is noted, switch to other phases.
- Meter could be bad.
- Reference phase could be mislabeled.
- Revenue meter:
  - Log in to DAS program.
  - Navigate program to compare programmed CT ratio to the ratio listed on the CTs.
  - Look at power factor of all three phases to confirm it is close to one with the system operating.
- Note that power factor may be low at startup or in low light conditions of less than 250 W/m<sup>2</sup>.
  - Confirm good phase rotation with system running.
  - Compare revenue grade data with inverter data, noting differences.
- Inverter direct:
  - Log in to DAS program.
  - Confirm system is checking in accurately.
  - Look at system history to confirm data is not intermittent.
- Intermittent data from inverters can be the result of noise induced by the inverter.
- Check that the recommended shielded cable is used for communication wiring.
- Check route of communication wiring to ensure it is away from voltage carrying conductors.
- Confirm shield is only landed in one spot; best to do this at the DAS enclosure.
- Confirm appropriate resistor or termination is installed in the last inverter in the chain (if required).
- Combiner box level monitoring:
  - Log in to DAS program.

- Confirm that all boxes are visible.
- Compare results to Imp string test results.
- Module level monitoring:
  - Log in to DAS program.
  - Confirm communication to all devices.
  - Shade individual modules to confirm module mapping is accurate.

### **8.17 Ground Fault Troubleshooting**

Ground faults can be difficult to troubleshoot, depending on the severity and location of the fault. However, steps can be taken to efficiently troubleshoot ground faults in a PV system.

#### *Test conditions*

- Testing can be done under any conditions with enough light to produce voltage. However, some fault conditions only occur when the system is wet or is moved to a particular angle, and may be difficult to troubleshoot without replicating those conditions.

#### *Tools include:*

- dc voltmeter;
- ohmmeter;
- replacement fuses;
- jumper wire USE-2 or PV Wire with male and female connectors compatible with the system;
- megohmmeter;
- PPE;
- screwdriver or combiner box key, if applicable;
- electrical tape;
- system drawings—string wiring diagram; and
- recording device (pen and paper, laptop preferred).

#### *Safety considerations include:*

- shock hazard, live voltages present;
- normally un-energized components may become energized under fault condition;
- fall hazard—combiner boxes and meteorological stations are often installed at heights of more than six feet and will require fall protection per OSHA requirements;
- proper PPE for electrical voltage testing;
- normally de-energized circuits may be energized in fault conditions; and
- requirement for two qualified people trained in CPR.

#### *Test procedure small residential-scale inverters*

- Turn inverter off at the on/off switch, if applicable.
- Turn off the dc and ac disconnect (may be the same switch).
- Remove and test the ground fault fuse continuity with an ohmmeter.
  - If the fuse is good, may not have a ground fault.
  - Verify by testing voltages to ground with the fuse removed. If within specifications, replace fuse and restart meter.
- If the fuse fails continuity test, there may be a ground fault.
  - Verify it is the correct rating type and size fuse.
  - In most small inverters, the fuse is the path to ground. When the fuse is

- removed from the system, the normally grounded conductor is no longer grounded.
- If the ends of the circuit are isolated, neither the ungrounded nor grounded strings should have a well-defined open circuit voltage when tested from the conductor to ground.
  - If a well-defined voltage is present, there may be a fault.
  - Small inverters usually have four or fewer inputs, so isolate the string with the fault by removing the fuses from the combiner box.
  - With the fuses removed, test for voltage from the line side of the fuse terminals to ground.
  - If voltage is present on all of the terminals to ground, isolate the normally grounded conductors by removing them from the bussing.
  - Repeat until the string with the fault is found.
  - Take the isolated string with the fault and record the voltage from the normally grounded conductor to ground and from the normally ungrounded conductor to ground.
    - If the voltage is equal to the full open circuit voltage of a string, then the fault is likely at the normally grounded end of the string.
    - If the voltage is a different value, then the fault is likely somewhere in the middle of the array or possibly in a module.
  - Determine the location of the fault by adding the  $V_{OC}$  of a single module one after another until it adds up to the voltage of the fault. For example, consider 10 modules in a string with a  $V_{OC}$  of 50 V<sub>dc</sub> each, with module one connected to the ungrounded homerun cable and module 10 connected to the grounded homerun cable. When testing at the combiner box from the line side of the ungrounded fuse holder to ground and the result is 100 V<sub>dc</sub> and testing from the ungrounded conductor to ground and the result is 400 V<sub>dc</sub>, then the fault is somewhere between the second and third module in the string. Given the same wiring as above but a reading of 0 V<sub>dc</sub> from the ungrounded side and 500 V<sub>dc</sub> from the grounded side, the fault is in the ungrounded homerun.
  - Given the above scenario, it would be wise to use a megohmmeter on all of the conductors in the conduit to make sure that the fault is isolated to the one homerun conductor.

#### *Test procedure—central type inverters*

- Turn inverter off at the on/off switch, if applicable.
- Turn off the ac and dc disconnect connected to the inverter.
- Remove and test the ground fault fuse continuity with an ohmmeter.
  - If the fuse is good, there may not be a ground fault.
  - Verify by testing voltages to ground with the fuse removed. If good, replace fuse.
  - If the fuse fails the continuity test, there may be a ground fault.
  - Verify it is the correct rating type and size fuse.
- For central inverters, the only fuse allowed in the grounded conductor is the ground fault interrupter fuse with an accompanying label, so removing the fuse will unground the grounded conductor.
  - Remove conductors one at a time, test the voltage to ground, and then put a wire nut or electrical tape around the end of the conductor.
  - Repeat until the string with the fault is identified. (Note: If the combiner box with the fault was not found, the next step is to use a megohmmeter to test the homerun wires from the combiner box back towards the inverter. It is

- possible to have a fault in the homerun wire from the combiner box to the inverter.)
- Take the isolated string with the fault and record the voltage from the normally grounded conductor to ground and from the normally ungrounded conductor to ground.
    - If the voltage is equal to the full open circuit voltage of a string, then the fault is likely at the normally grounded end of the circuit.
    - If the voltage is a different value, then the fault is likely somewhere in the middle of the array or possibly within a module.
  - Determine the location of the fault by adding the  $V_{OC}$  of one module after another until it adds up to the voltage of the fault. For example, consider 10 modules in a string, with each module having a  $V_{OC}$  of 50 V<sub>dc</sub>. Module one is normally the ungrounded homerun and module 10 is normally the grounded homerun. If a test at the combiner box from the line side of the ungrounded fuse holder to ground results in 100 V<sub>dc</sub>, and the test from the ungrounded conductor to ground results in 400 V<sub>dc</sub>, then the fault is somewhere between the second and third module in the string. Given the same wiring as above but a reading of 0 V<sub>dc</sub> from the ungrounded side and 500 V<sub>dc</sub> from the rounded side, the fault is in the ungrounded homerun.
  - Given the above scenario, it would be wise to use a megohmmeter on all of the conductors in the conduit to make sure that the fault is isolated to the one homerun conductor.

### **8.18 Array Washing Procedure**

Depending on the site conditions, an annual or even quarterly cleaning may pay for itself in gained production. Some sites have more accumulation of dirt and other buildup than other sites. Depending on the tilt of the array and amount of seasonal rainfall, the soiling can have a dramatic impact on the overall production of the system. Most module manufacturers have specific guidelines about how not to clean modules, such as not using high pressure water, not using harmful chemicals, and even not using cold water when the module glass temperature is hot or using hot water to clean cold modules. Thermal shock from the difference in temperature between the glass surface temperature and the water temperature can result in fracturing or breaking of the glass.

#### *Safety Considerations*

- Wear rubber sole shoes with good traction to prevent slips and falls.
- Never walk on the modules. Use non-conductive extended reach broom and hose handles to reach modules
- A lift may be needed to access the array. Follow aerial lift safety procedures, including wearing a harness if required.

#### *Before Washing Modules*

- Walk the site to confirm that there are no broken modules (shattered glass). Never spray broken modules with water. Perform a safety evaluation of the site looking for safety hazards such as trip hazards or areas that will become excessively slippery when wet.
- Plan for water runoff. If the site has a storm water prevention plan in place, determine how the used water will be collected and disposed of. If harmful chemicals are not used during the cleaning process, drain guards can be used to

filter out sediments.

- Be aware of trip hazards introduced by having hoses spread throughout the property, cone off area if needed.
- Determine whether the module cover glass is too hot and will be damaged by coming into contact with cool water. Depending on the local climate and time of year, it may be best to limit washing activities to the morning or evening hours.
- Identify the water source to be used. Ideally, there will be a source of water near the array. If not, it may be necessary to bring in water from an outside source, which will involve a tank or water truck.
- Determine the best method of getting water to the modules. Typically, a
- $\frac{3}{4}$ -inch garden hose is used to connect to a spigot near the array.
- Set up hoses and tools.
- If required, block or install drain guards for filtration or water capture purposes.
- Take a baseline production reading of the system, noting both kilowatt-hour (kWh) output of each of the inverters and weather conditions including temperature and irradiance.

#### *Washing Modules*

- De-ionized water is preferred to prevent spotting and calcium buildup.
- Normal water pressure of 50 to 70 pounds per square inch is recommended;
- do not use high pressure washers.
- If high pressure washers are necessary, hold the pressure source far enough away from the modules to prevent damage. As a rule of thumb, if the stream is too strong to comfortably hold one's hand in, it is too much pressure for the modules.
- Spray the modules with water.
- Use a soft-bristled brush to get stubborn dirt off.
- If needed, use a non-damaging soap.
- Use extensions with tools to be able to reach extended distances.
- If needed, squeegee modules dry.

#### *After Washing Modules*

- After the system returns to steady-state temperature (i.e., there is no remaining impact from the cooling effect of wash water), take another production reading of the system, noting both kWh output of each of the inverters and weather conditions including temperature and irradiance.
- Clean up tools.
- Remove any drain guards or blocks.
- Record the washing in the maintenance log.
- Compare production of the clean system to the previous production values.

### **8.19 Vegetation Management**

Vegetation management is particularly important in ground mount systems, but is a concern for all PV systems. Vegetation can grow into and cause problems with trackers, can cause problems with array wiring, and can cause shading, which will definitely impact production but could also cause damage to an operating system. Vegetation should also be controlled around the inverter pad and other areas where electrical equipment is present. Note: PV arrays are often home to snakes, bees, and venomous animals of all kinds. Wear protective clothing and be alert for possible encounters.

### *Safety Considerations*

- Wear rubber soled shoes with good traction to prevent slips and falls.
- Wear PPE to prevent bites and stings from insects, snakes, and vermin.

### *Vegetation Management*

- Mowing or weed trimming vegetation around a ground mount can lead to problems if the mowing or weed trimming kicks up debris that can break the glass or cause general soiling that results in underperformance.
- Poisoning weeds can lead to environmental and health problems.
- Permanent abatement at the time of installation is the ideal way to deal with vegetation management.
- During inspections, note the amount of vegetation growth and document it through pictures.
- Work with the site owners to come up with a specific vegetation management plan that involves carefully removing or cutting back vegetation that is currently shading or will eventually grow to shade parts of the array.

## **8.20 System Warranties**

It is important to know and understand the warranty requirements of the specific products used in a PV system. Not all warranties are created equal. Warranty requirements not followed, including documenting regularly conducted preventive maintenance, can result in a voided warranty. Typical warranty requirements are strict regarding the tasks that must be performed. However, the tasks are often simple and serve to protect the products and ensure greater long-term reliability.

## **9. CONCLUSIONS**

The rapid expansion of photovoltaic installations underscores the growing need for robust operations and maintenance (O&M) practices that ensure long-term system safety, performance, and reliability. As PV systems continue to evolve toward higher voltages, larger scales, and longer lifespans, the role of qualified and properly trained personnel becomes increasingly critical. Ensuring adherence to established safety protocols—including proper signage, lockout/tagout procedures, and the use of appropriate personal protective equipment—remains essential for mitigating risk and protecting both technicians and system integrity.

Effective O&M also plays a vital role in maximizing system uptime, optimizing return on investment, and ensuring consistent energy production. Detailed procedures for inverter troubleshooting, fault detection, string testing, data acquisition verification, and preventive maintenance help address performance issues before they escalate. Strategies such as stocking critical replacement parts and maintaining accurate documentation further support timely system recovery and long-term operational success.

As the PV industry continues to expand, coordinated efforts from industry groups, researchers, manufacturers, and field technicians will be necessary to standardize best practices and develop comprehensive O&M frameworks. This paper provides an introductory foundation for understanding the essential tools, techniques, and safety considerations that underpin effective PV system maintenance. With continued advancements and a commitment to operational excellence, photovoltaic systems will remain a reliable and indispensable component of the global clean energy landscape.

The final conclusions to this paper include:

- To maintain quality control and safety standards, it is important that only qualified personnel work on PV installations. It is not always easy, however, to identify qualified personnel. The authors suggest skill and knowledge guidelines for PV technicians in the Qualified Personnel section of the INTRODUCTION chapter.
- Safety is a serious concern when servicing PV installations. Early PV systems often had maximum system voltages less than 50 Vdc, but 600 Vdc systems are now common, and 1,000 Vdc systems are allowed by code in commercial and large-scale installations. Safety considerations require that qualified personnel use properly rated equipment and be trained for servicing the higher voltage systems.
- Qualified personnel should always work in teams of two people when working on live equipment. In addition, on a given jobsite, there should always be at least two qualified persons trained in CPR.
- Not all installations have appropriate signage, and qualified persons must be trained to recognize potential hazards with or without signage present.
- System uptime and availability is a key objective of O&M. Inverters that are offline can have a dramatic negative impact on the ROI of a PV system. Inverter failure rates are important to ROI, but even more important than how often an inverter goes offline is how quickly it can be placed back into service.
- Low power production also impacts ROI, and O&M personnel need effective strategies for identifying and correcting problems quickly. One specific recommendation is to stock critical parts that have long supply lead times.

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## ENERGY CHARACTERIZATION AND OPTIMIZATION OF DENSIFIED SAWDUST BIOMASS WITH DIFFERENT TECHNIQUES

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### ABSTRACT

Sawdust is a common biomass waste product, but its high moisture content and low bulk density make it difficult to handle, transport, store, and burn efficiently. By physically compacting the material into a consistent, high-density biofuel, densification procedures like pelletization and briquetting are used to get around these restrictions. The impact of different densification settings and methods on sawdust's mass-basis energy content (calorific value) and volumetric energy density is examined in this study. Several techniques were investigated, such as the incorporation of thermal pre-treatments and basic mechanical compaction with different pressures. The purpose of this sawdust densification study was to compare the screw press and piston press using identical electric motors (1 HP), driver/driven pulleys, v-belts, cylinders (barrels), and extrusion die. Because the densification presses were designed using the extrusion principle, a prototype of each press was made using locally accessible materials such as aluminium alloy, brass, mild steel, and galvanized sheet. The average calorific value (HHV) or mass energy density of the screw press's output briquettes was found to be 20048 KJ/kg. The average calorific value of the raw sawdust was 18682 KJ/kg, but the briquettes from the piston press had an average of 19244 KJ/kg.

### 1.0 INTRODUCTION

Biomass densification represents a set of technologies for the conversion of biomass into a fuel. The technology is also known as briquetting and it improves the handling characteristics of the materials for transport, storing etc. This technology can help in expanding the use of biomass in energy production, since densification improve the volumetric calorific value of a fuel, reduces cost of transport and can help in improving the fuel situation in rural areas. Raw materials for briquetting include waste from wood industries, loose biomass and other combustible waste products (Tanimu et al., 2013).

In most of Nigeria, biomass has maintained an all-time high level of acceptance for home cooking due to its affordability and accessibility. Nevertheless, there are limitations on using biomass as a direct fuel for power generation despite these advantageous characteristics. High

particle wetness, low energy density, hydrophobicity, high oxygen content, and smoke production above the permissible limit for residential uses are a few of these. Due to its abundance and high energy content, biomass has become a viable alternative energy source in light of the growing expense, scarcity, and environmental risks associated with fossil fuels. (Bello et al., 2023)

One of the most important energy sources of mankind is biomass which is referred to all organic materials particularly wood and agricultural residues. It accounts for approximately 14% of total energy consumption in the world. It is widely accepted that fossil fuel shortage, fuel increase price, global warming including other environmental problems are critical issues. Therefore, sawdust energy has been attracting attention as an energy source since zero net carbon dioxide accumulation in the atmosphere from sawdust briquettes production and utilization can be achieved (Potomsok, 2007)

While biomass is a great renewable energy source, it is not a good fuel, because it typically contains more than 70% air and void space. This low volumetric energy makes it difficult to collect, ship, store and use. Densification is a relatively new process in which the air is squeezed out at high pressure to make briquettes (solid fuel) (Fapetu, 2000).

Fuel is defined as natural or artificial organic substance used as source of energy and raw material for domestic and industrial uses. Solid fuel for which bound or compressed sawdust (briquettes) belongs is grouped under the natural fuel origin (Gupta and Poonia, 2004). A fuel is any material that is burnt or altered to obtained energy. Fuel releases it energy either through chemical means, such as combustion or nuclear means, such as nuclear fission.

Sawdust is a common form of briquetting material. It is found throughout the world. In general anything that burns but is not found in an easy-to-use size can be used to make briquettes (Jekayinfa and Omisakin, 2005).

The availability of energy for domestic use in Nigeria continues to pose a formidable challenge, especially with the high cost of cooking gas and kerosene and the environmental problems associated with firewood. Alternative forms of energy need to be sourced. This has necessitated the need to improve on the use of biomass wastes such as sawdust as alternative energy (Oladeji, 2010).

The first step in briquetting is to collect a large amount of the material. Then the material is cut or crushed to make it smaller. Next it is combined with a small amount of water and a binder that keeps the material from falling apart when the pressure is taken away. Clay, mud, cement and starch are commonly used binders (Gary, 2004).

### **1.1 Densification Techniques**

Densification techniques enhance the energy content of sawdust by increasing its volumetric energy density and improving its combustion properties. This is primarily because the process compacts the material, making it denser and more efficient for storage, transportation, and fuel use. While densification itself primarily improves physical characteristics like density and durability, pre-treatment steps like torrefaction can further increase the energy content per unit volume.

## **1.2 Effects of Densification on Energy Content**

Increases volumetric energy density: Compacting sawdust into pellets or briquettes significantly increases its density, meaning more energy is packed into the same volume. Improves handling and storage: The higher density makes the fuel easier and cheaper to transport and store, which is a major advantage over low-density raw sawdust. Enhances combustion properties: Densification improves the fuel's durability and water-resistance, leading to more efficient and reliable combustion (Tanimu et al., 2013). Enables coal substitution: The improved energy density and properties make densified sawdust a viable alternative fuel that can be co-fired with coal in power plants.

High compaction technology or binderless technology consists of the piston press and the screw press. In the piston press technology, the biomass is pressed in a die by a reciprocating ram at a high pressure (Ojo and Mohammed, 2015). The piston press acts in a discontinuous fashion with material being fed into a cylinder which is then compressed by a piston into a slightly tapering die. However, in the screw press technique, material is fed continuously into a screw which forces the material into a cylindrical die (Tanimu et al., 2013); this die is often heated to raise the temperature to the point where lignin flow occurred (Grover and Mishra, 1996).

Densification technique will provide a means of reclaiming valuable secondary and high energy raw materials from process or production waste to achieve the following applications:

- Recycling
- Shredding
- Reduction of volume
- Making fuel “log”
- Removing water and oil
- Recovery of valuable materials.
- Gasification of biomass
- Compaction of filter dust

## **1.3 Objectives**

The main objectives of this research are:

- a) To determine the merits and demerits of the two densification techniques operated on the sawdust.
- b) To establish a suitable and easier method of upgrading and converting wood residues into solid fuel for domestic and industrial uses thereby keeping the environment clean.

## **2.0 RELATED LITERATURES**

### **2.1 The Energy Potential of Sawdust**

Sawdust waste has been fired in boilers in a number of industries for many years both as means of waste disposal and of energy recovery (Gunn and Robert, 1989). But collection, transporting and firing the raw sawdust was a common problem. Europe had made every effort to further diversify its energy resources and to conserve energy, thus a significant energy potential was achieved from sawdust, e.g. the total net energy potential (after conversion) of forestry/wood residues was  $3.33 \times 10^8$  GJ –  $1.8 \times 10^9$  GJ (Bridgwater, 1997).

The compaction of loose combustible material for fuel making purposes was a technique used by most civilizations in the past, though the methods used were no more than simple bundling, baling or drying. Industrial method of briquetting dates to the second part of the 19<sup>th</sup> century.

In 1865, a report was made on a machine used for making fuel briquettes from peat which is a recognizable predecessor of current machines (Grover and Mishra, 1996). Compacted biomass can be used as fuel in semi-urban and rural areas. Densification allows biomass resources to have a higher density and lower volume. Numerous studies on briquettes have shown an increase in the amount of densified sawdust or other biomass generated (Ikubanni et al., 2019).

Biomass is the world's third-largest source of energy among all renewable resources. Materials and lining materials can be biologically transformed into matter by biomass. Low-density biomass residues are difficult to handle, transport, store, and burn. A major factor in reducing the issue of large storage capacity and convenient transportation is densification/briquetting technology. The best way to use raw agricultural waste as a solid biomass fuel is with briquettes or pellets (Sunny et al., 2022).

### **3.0 MATERIAL AND METHOD**

This research work was conducted by producing sawdust briquettes as solid fuel by using starch as a binder with the two densification techniques. Prototypes of the two briquetting machines were constructed tested, and their performances were determined. The following sequence was used (Tanimu et al., 2013).

#### **3.1 Collection of raw sawdust and pre-processing of the raw sawdust:**

There are many factors to consider before a biomass qualifies for use as feed stock for densification (briquetting). Apart from its availability in large quantities, it should have the following characteristics as feed parameters, these includes (Grover and Mishra, 1996):

- (a) Effect of Moisture (Low moisture content, range of 10 - 15%)
- (b) Effect of Particle size
- (c) Effect of Ash content (Low ash content, range of 20 - 22%)
- (d) Effect of Temperature of Biomass
- (e) Effect of Temperature of the Die
- (f) Effect of External Additives
- (g) Hardness

#### **3.2 The Briquetting Machines (Presses)**

These are the cold extrusion equipment used in the production of the sawdust solid fuel as shown in Appendix I. They were fabricated with locally available materials like mild steel, galvanized sheet, aluminium alloy and brass after a careful material selection procedure.

##### *3.2.1 Size of Cylinder (Barrel), Length of Stroke and Crank Plate Diameter:*

The size of the briquettes produced were 40mm diameter, thus the piston sleeve of a Peugeot 504 car was used with an internal diameter of 84mm. The total length of the cylinder is 200mm, and then the length of stroke is 125mm. Therefore, the crank plate diameter is equal to 125mm equivalent to the length of stroke (Shah, 1965).

##### *3.2.2 Size of Driven Pulley and Driven Pulley Speed:*

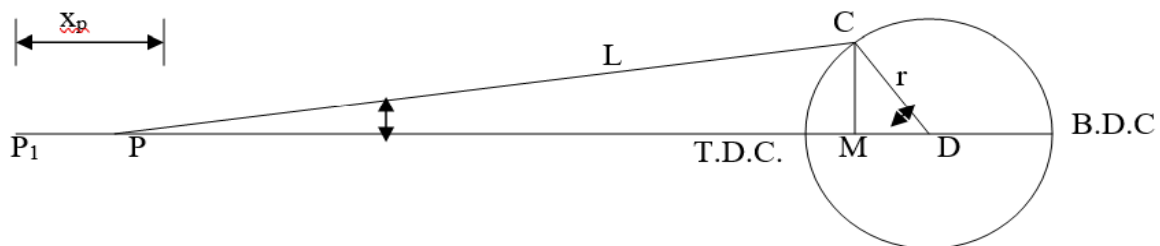
The speed of the driven pulley was calculated (in ratio 1:5.6) and reduced to 250rpm from 1400rpm of the driver pulley (motor) speed. This enable the presses not to act as compressors especially the piston press, thus the diameter of the driven pulley was larger than the diameter of the driver pulley. This was calculated from; (Gupta and Poonia, 2004)

$$\text{Driven pulley speed (rpm)} = \text{Driver pulley speed (rpm)} \times \frac{\text{diameter of driver pulley}}{\text{diameter of driven pulley}}$$

With driver pulley diameter of 46mm, the driven pulley diameter was determined as 258mm and approximately in cm its ( $\approx 26$ cm)

### 3.2.3 Length of connecting rod and size of the piston:

The approximate analytical method was used to determine the velocity and acceleration of the piston with reference to the line diagram shown in figure 1; (Shah, 1965). This shows the arrangement of the piston-connecting-rod and crank mechanism as seen below (Figure 1).



**Figure 1.** Piston – Connecting – Rod and Crank Mechanism

With reference to the known length of stroke of the piston, the length of cylinder, the crank diameter and the cylinder internal diameter, a line diagram of a link-mechanism consisting of the piston, crank and connecting rod was drawn. Knowing the initial position of the piston and the other parameters above, the length of the connecting rod was established as 175mm using link-mechanism construction on paper. The piston was casted to the size of  $\varnothing 83$ mm by 125mm to accommodate the required length of stroke (125mm) of the piston press.

### 3.2.4 The feed screw (Auger) on the screw press:

This is the prime transporter of the material for briquetting on the screw press. A mild steel flat bar of 2 mm thickness was notched with V-shaped through a length long enough to cover the screw shaft i.e. 160mm out of the 200mm length of the barrel. The distance between each flight of the auger is 30mm. The auger (screw feeder) runs with an equivalent speed of the driven pulley, which is 250rpm.

### 3.2.5 Extrusion Die:

These were produced in two numbers with all dimensions and features equal. They are the head of the densification presses whereby the briquettes takes and form the shape of the die ( $\varnothing 40$ mm) (Tanimu et al., 2013)

## 3.3 The Preparation and Production of the Sawdust Briquette

The first step in briquetting is to collect a large amount of the material. Then the material is crushed to make it smaller. Screening of feed material is essential for materials like sawdust which may contain many wooden cut pieces (Sheng, 2004). Next it is combined with a small amount of water and a binder that keeps the material from falling apart when the pressure is taken away. Clay, mud, cement and starch are commonly used binders (Gary, 2004).

The basic pre-processing steps are sieving-drying-mixing-densification & drying the briquettes. For every 3kg of screened sawdust, 1.5litres of starch was used for mixing. Starch was used because it's an organic binder, organic binders usually increase the heat value of wood briquettes and do not add to their ash content, thus briquettes made with some of these organic binders do not soften or disintegrate during combustion (Yahaya and Ibrahim, 2007).

### 3.3.1 Factors That Influence Energy Content

- a) *Moisture content*: Lower moisture content in the raw material leads to higher compression strength and density, which correlates with higher energy content.
- b) *Temperature*: Applying heat during the densification process improves the final product's physical, mechanical, and energetic characteristics.
- c) *Pressure*: While pressure has some influence, its effect on strength is less pronounced than that of temperature or moisture content.
- d) *Binders*: Adding binders can improve the physical and chemical properties, including the energy content, of the densified product.
- e) *Pre-treatment (Torrefaction)*: Pre-treating sawdust with heat before densification like torrefaction can further increase its energy density and durability.

### 3.3.2 Economic Advantage in the use of Binders

The binding agency must produce a briquette of sufficient toughness to withstand exposure and the shocks of storage, transportation and stocking. Exposure to weather must not cause crumbling or excessive softening, and during combustion the exposure to heat must not cause disintegration (Yahaya and Ibrahim, 2007).

## 3.4 Instrumentations and Materials

### 3.4.1 Raw material:

Sawdust (Dried to 10 - 16% moisture content) and the use of Starch  
(Locally made – wet)

### 3.4.2 Equipment used and their Manufacturers:

Stopwatch (GT4, Japan), Fabricated stove with Ash tray, Vanier Caliper, Thermometer (THERMEX), Digital Thermometer (0–2001range-comark, N.York), Weighing scale (Horse-race scale,U.S.A), Digital Scale (B303 College Digital balance), a standard pot (2.5 liters) and Bomb Calorimeter.

## 3.5 Briquettes Measurements and Comparison from Screw Press & Piston Press:

After the construction and fabrication of the prototype of the two presses, they were tested satisfactorily. The following were observed for their comparison, which are the two densification techniques. these includes wear of parts, noise, output from the machines, maintenance, density of briquette, homogeneity of briquette, friability, resistance to humidity, temperature of briquette and the combustion characteristics (calorific value).

## 4. RESULTS AND DISCUSSION

It was observed that the output briquettes from the screw press was continuous (12kg/hr –wet basis) while that of the piston press was in stroke (9kg/hr –wet basis). After sun drying the sample briquettes as shown in Appendix II, they were observed, measured and analyzed. On the dry basis the briquettes from the screw press have less diameter, greater mass and density but those from the piston press have greater diameter, greater volume, less mass and density.

**Table 1.** Density of Briquette from Screw Press

Sample	$\phi$ (mm)	$r$ (mm)	$h$ (mm)	$m$ (g)	$v$ (m <sup>3</sup> )	$\rho = \frac{m}{v}$ (g/m <sup>3</sup> )	$\rho$ (kg/m <sup>3</sup> )
1	37.5	18.75	69	30.30	76.22	0.398	3.98x10 <sup>-4</sup>
2	37.0	18.50	69.5	30.30	74.74	0.405	4.05x10 <sup>-4</sup>
3	36.5	18.25	70	30.24	73.25	0.413	4.13x10 <sup>-4</sup>
4	36.0	18.00	69.5	30.16	70.24	0.429	4.29x10 <sup>-4</sup>
5	37.0	18.50	69.5	30.24	74.74	0.405	4.05x10 <sup>-4</sup>
Total	184	92	347.5	151.24	369.19	2.05	20.5x10 <sup>-4</sup>

Average	36.8	18.4	69.5	30.25	73.84	0.41	$4.1 \times 10^{-4}$
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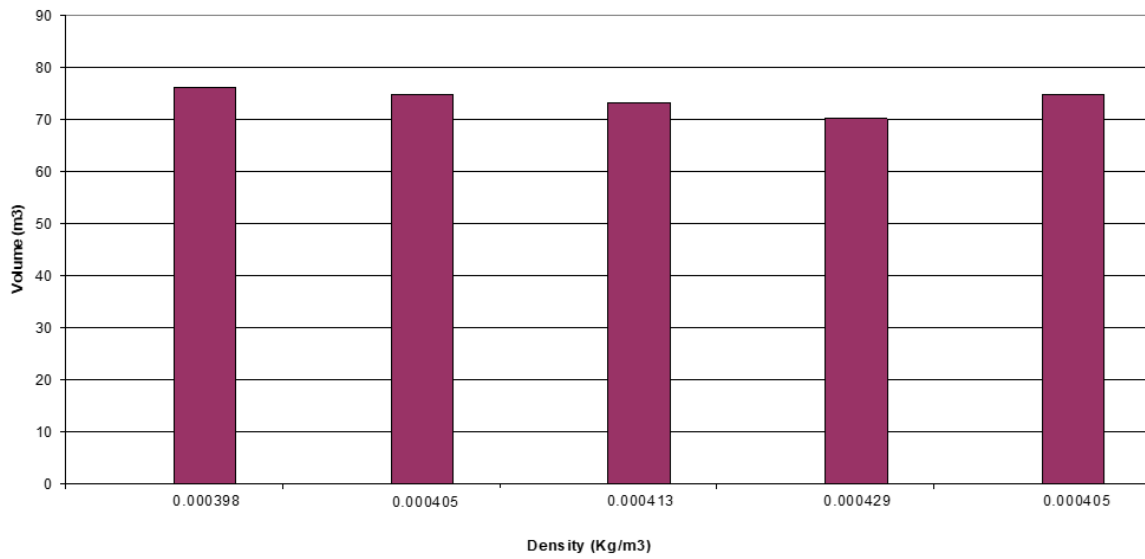


Figure 2. Volume against Density of Briquette from Screw Press

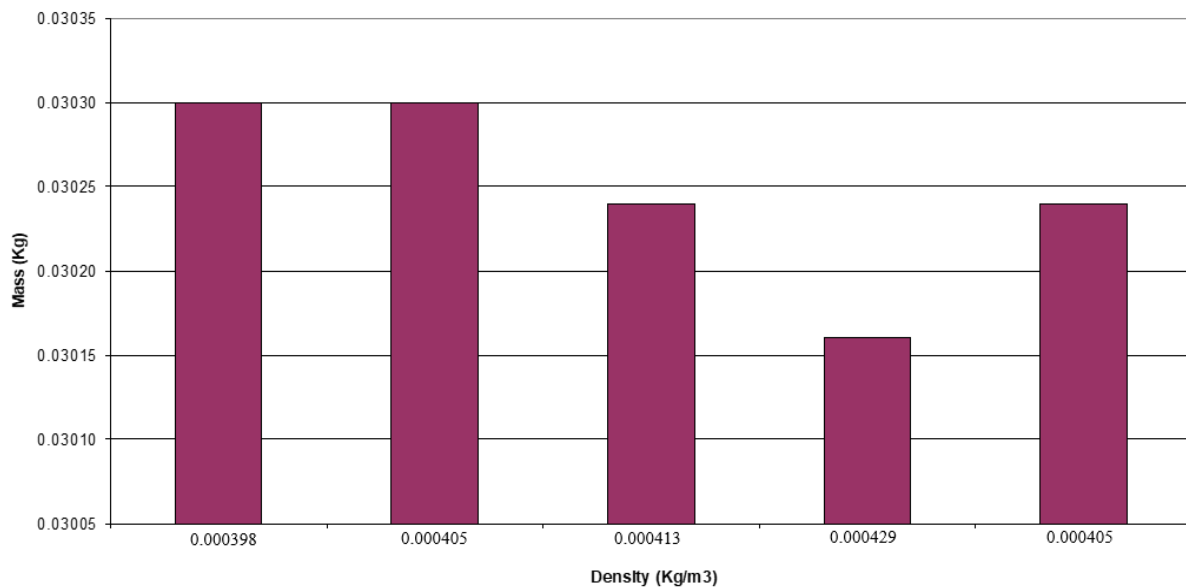


Figure 3. Mass against Density of Briquette from Screw Press

Table 2. Density of Briquette from Piston Press

Sample	$\phi$ (mm)	$r$ (mm)	$h$ (mm)	$m$ (g)	$v$ (m <sup>3</sup> )	$\rho = \frac{m}{v}$ (g/m <sup>3</sup> )	$\rho$ (kg/m <sup>3</sup> )
1	38.70	19.35	69	29.50	81.17	0.339	$3.39 \times 10^{-4}$
2	38.00	19.00	69.5	26.60	78.83	0.337	$3.37 \times 10^{-4}$
3	38.50	19.25	68.5	26.65	79.76	0.334	$3.34 \times 10^{-4}$
4	37.50	18.75	69	25.95	76.22	0.341	$3.41 \times 10^{-4}$
5	38.50	19.25	69	26.70	80.84	0.332	$3.32 \times 10^{-4}$
Total	191.2	95.60	34.5	133.4	396.32	1.683	$16.83 \times 10^{-4}$
Average	38.24	19.12	69	26.7	79.3	0.34	$3.34 \times 10^{-4}$

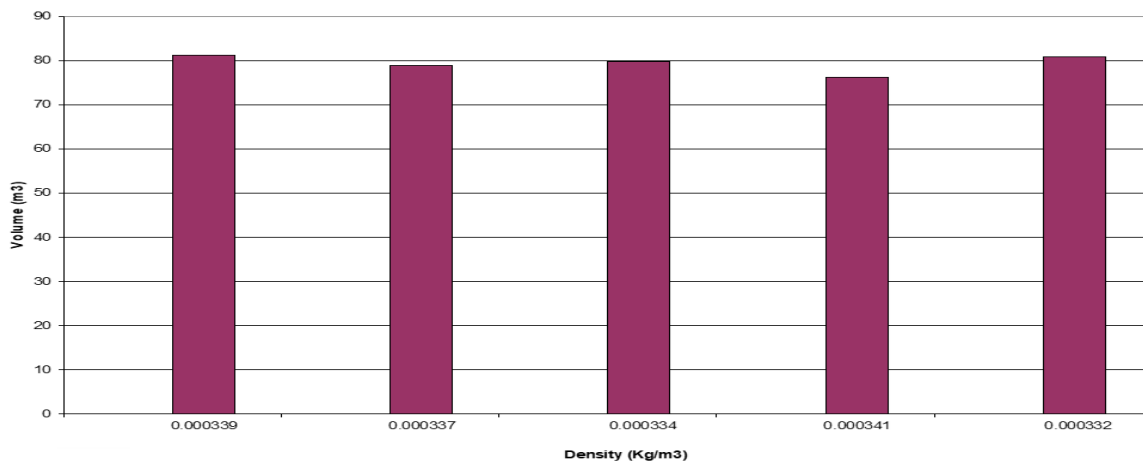


Figure 4. Volume against Density of Briquette from Piston Press

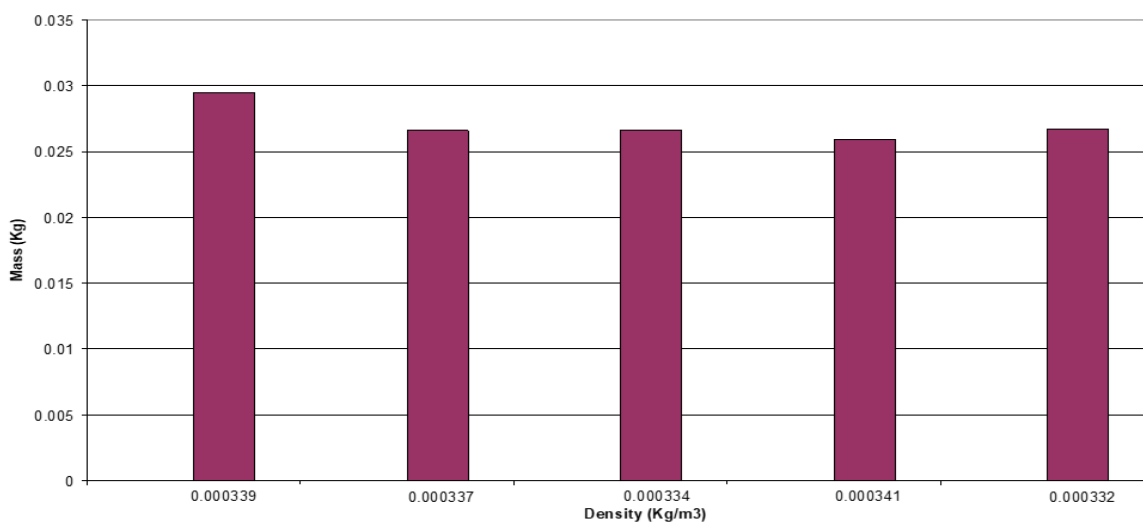


Figure 5.: Mass against Density of Briquette from Piston Press

#### 4.1 Briquette Durability (friability) - (CRA, 1987)

Tests were done after samples of briquettes were dried.

Where  $H = 10\text{ft} = \text{the chosen height for the test where the samples were dropped}$   
 $= (10 \times 0.3048) = 3.05\text{m}$

$a$  = briquette durability index

$m_a$  = briquette remaining (g)

$m_e$  = original wt. (g)

$m_p$  = briquette wt. after the test (g)

Table 3. Durability of Briquette from Screw Press

Sample	$H(m)$	$m_e(g)$	$m_p(g)$	$m_a = m_e - m_p(g)$	$a = \frac{m_a}{m_e} \times 100(\%)$
1	3.05	30.25	29.87	0.38	1.26
2	3.05	30.30	29.99	0.31	1.02
3	3.05	30.16	29.86	0.30	0.99
4	3.05	29.98	29.63	0.35	1.17
5	3.05	30.30	30.29	0.01	0.03

**Table 4.** Durability of Briquette from Piston Press

Sample	$H(m)$	$m_e(g)$	$m_p(g)$	$m_a = m_e - m_p(g)$	$a = \frac{m_a}{m_e} \times 100(\%)$
1	3.05	25.86	25.38	0.48	1.86
2	3.05	26.72	26.24	0.48	1.80
3	3.05	27.02	27.00	0.02	0.07
4	3.05	26.60	26.05	0.55	2.07
5	3.05	26.65	26.29	0.36	1.35

#### 4.2 Briquette Resistance to Humidity (CRA, 1987)

Where  $\phi_i$  = initial briquette diameter (mm)

$\phi_f$  = final briquette diameter (mm)

$T_e$  = elongation time (min)

e = elongation (mm)

**Table 5.** Resistance to Humidity of Briquette from Screw Press

Sample	$\phi_i$ (mm)	$\phi_f$ (mm)	$T_e$ (min)	$e = \phi_f - \phi_i$ (mm)	Percentage Elongation per min (%) $\frac{e}{T_e} \times 100$
1	36.6	40.0	15	3.4	22.7
2	37.2	40.2	15	3.0	20.0
3	37.5	40.9	15	3.4	22.7
4	36.5	40.1	15	3.6	24.0
5	36.0	39.9	15	3.9	26.0

**Table 6.** Resistance to Humidity of Briquette from Piston Press

Sample	$\phi_i$ (mm)	$\phi_f$ (mm)	$T_e$ (min)	$e = \phi_f - \phi_i$ (mm)	Percentage Elongation per min (%) $\frac{e}{T_e} \times 100$
1	38.1	42.2	15	4.1	27.3
2	37.9	41.9	15	4.0	26.7
3	38.5	42.9	15	4.4	29.3
4	38.0	42.4	15	4.4	29.3
5	38.6	43.1	15	4.5	30.0

#### 4.3 The Water Boiling Test (WBT)

This modified version of the well-known Water Boiling Test is a rough simulation of the cooking process that is intended to understand how well energy is transferred from the fuel to the cooking pot. The modified version is WBT Version 3.0, Jan. 2007 (Rob, D. O., et al., 2007)

##### 4.3.1 Percentage Ash Content

$$\text{Percentage ash content} = \frac{\text{Mass of ash}}{\text{Total mass of fuel}} \times 100$$

**Table 7.** Briquette Percentage Ash Content

Test	Briquette from Screw Press			Briquette from Piston Press		
	Mass of Fuel Consumed (g)	Mass of Ash (g)	Ash Content (%)	Mass of Fuel Consumed (g)	Mass of Ash (g)	Ash Content (%)
WBT1	1200	57.6	4.8	1425	122.55	8.6
WBT2	1202	63.71	5.3	1405	123.64	8.8

#### 4.4 Calculated results of the Piston Velocity

The piston velocity for the length of stroke was calculated at an interval of 45°.

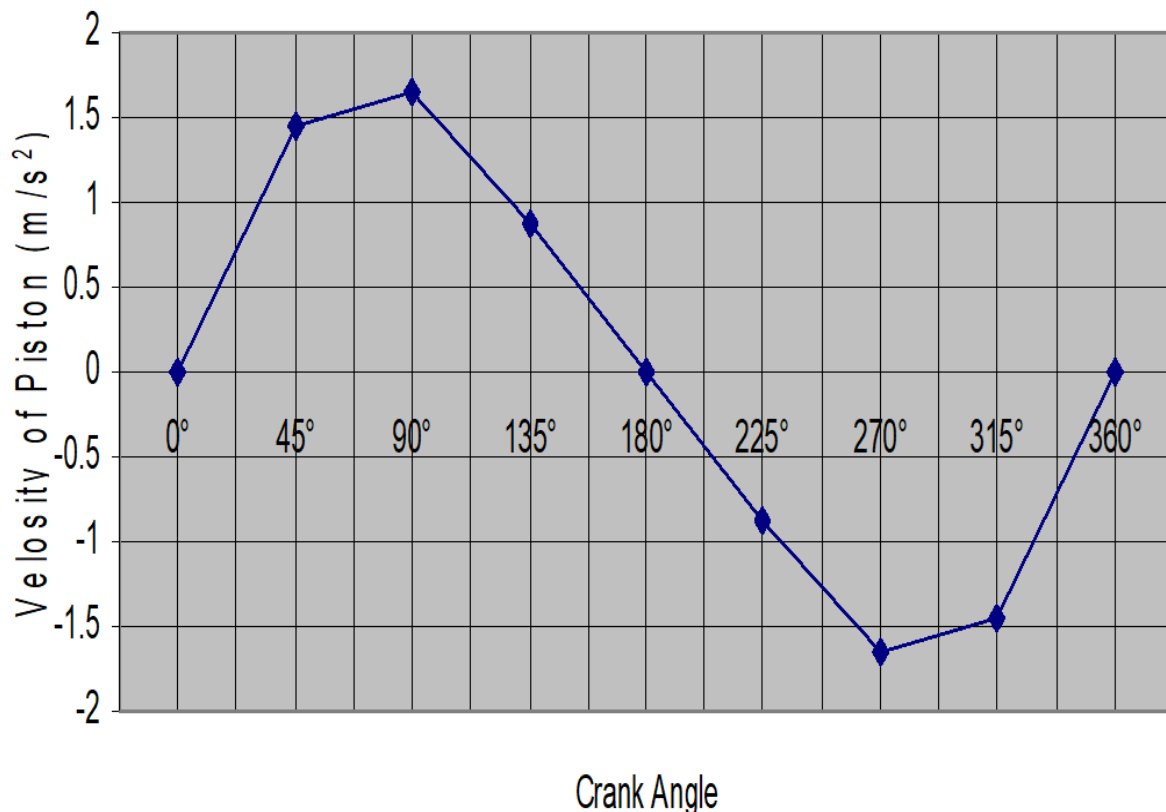
At  $\theta = 0^\circ$

$$\begin{aligned} \text{From this equation; (Shah, 1965): (a) } V_p &= \omega r \left[ \sin \theta + \frac{\sin 2\theta}{2n} \right] \\ &= 26.4 \times 62.5 \left[ \sin 0 + \frac{\sin 0}{2 \times 2.8} \right] \\ &= 1650 (0 + 0) \\ &= 0, \text{ e.t.c} \end{aligned}$$

The results are presented in the following table below:

**Table 8.** Velocity of Piston for the Various Positions of the Crank Obtained

$\theta$	0°	45°	90°	135°	180°	225°	270°	315°	360°
$V_p$ (m/s)	0	1.46	1.65	0.87	0	-0.87	-1.65	-1.46	0



**Figure 6.** A Graph of Velocity of Piston Vs Crank Angle

Consequently, from the test conducted with the oxygen Bomb calorimeter, briquettes from the screw press were found to have a greater average Gross calorific value (HHV) or mass energy density of 20048 KJ/kg. The briquettes from the piston press have an average calorific value of 19244 KJ/kg while the raw sawdust had an average calorific value of 18682 KJ/kg. The friability of the briquettes from the screw press has an index of 1% while briquettes from piston press have an index of 1.35 – 2%. An acceptable value of briquette quality has an index of 0.5 – 1.5%, 0 index implies that the briquette is likely to disintegrate entirely with time. Also, the percentage elongation per minute is less on the briquettes from the screw press compared to that of the piston press. A figure of less than 50% is acceptable quality (CRA, 1987). Thus, the briquettes from the screw press have higher resistance to humidity.

Other results are summarized and tabulated as follows:

**TABLE 9.** Summary of the Comparison of a Piston Press and a Screw Press Densification Technique on Sawdust biomass.

S/No	Comparison	Piston Press	Screw Press
1.	Optimum Moisture Content of Raw Material	Can operate with 10-17%	10 – 15%
2.	Vibration/Noise	High	Low
3.	Maintenance	High	Low
4.	Combustion performance of briquettes	Not good	Very good
5.	Density of briquette	0.332 – 0.341 g/m <sup>3</sup>	0.3908 – 0.405 g/m <sup>3</sup>
6.	Mass of briquette	23.95 – 27.50 g	30.16 – 30.30 g
7.	Volume of briquette	76.22 – 81.17m <sup>3</sup>	70.24 – 76.22 m <sup>3</sup>
8.	Output from the machine	In stroke	Continuous
9.	Homogeneity of briquettes	Non-homogeneous	Homogeneous
10.	Wear of contact parts	Low in case of piston	High in case of screw
11.	Calorific value of briquette	Low	High

## 5. CONCLUSIONS

In conclusion, while mechanical densification primarily improves the physical properties and volumetric energy, pre-treatments like torrefaction or carbonization are necessary to enhance the specific mass-basis energy content of sawdust, creating a high-quality solid biofuel. Other advantages include;

- i) In the application of sawdust as solid fuel, forming briquettes facilitates handling, storage and transportation.
- ii) The densification techniques increase the net calorific value of sawdust per unit mass
- iii) The briquetting process can help to solve the problem of wood residues disposal.
- iv) The screw press densification technique produced stronger, uniformly-sized and dense briquettes which are recommended for carbonization. Although the carbonized charcoal produced are brittle.
- v) The finished briquettes from the piston press need much protection from re-absorption of moisture than the briquettes from the screw press. This is because they are less dense and should be stored in dry areas. They need much careful handling to prevent crumbling.

- vi) Densification of sawdust using the screw press can be easily employed to set up a small-scale factory. This is because its output is continuous and the briquette is uniform in size. The screw press also runs very smoothly without much noise, and the machine is light compared to the piston press because of the absence of reciprocating parts and crank plate.

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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 I



Front view Photograph of the two Presses before painting



Front view Photograph of the two Presses after painting

## **APPENDIX II**



**Sample of Briquettes from Screw Press**



**Sample of Briquettes from Piston Press**



## AN OVERVIEW OF TRANSFORMING NIGERIA'S ENERGY FUTURE WITH SOLAR POWER AND HARNESSING THE ENERGY OF THE SUN FOR ELECTRICITY GENERATION.

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### ABSTRACT

*A brief review of ways of converting solar energy to electricity, directly and indirectly, is made, with a treatment of costs, estimates, viability and prospects. Nigeria's geographical location between 4° and 14° N latitude endows it with substantial solar resources. Depending on the region, the country receives between five and seven hours of daily sunlight, translating to high technical potential for photovoltaic energy generation. Data from global atlases confirms significant Global Horizontal Irradiation (GHI) and Direct Normal Irradiation (DNI) across the territory, providing a solid foundation for solar PV power potential (PVOUT). The case of Nigeria is analyzed with such factors as her resources, finances and geography in mind. Reasonable paths of implementation are then suggested in the light of the foregoing.*

### 1. INTRODUCTION

The last decade has witnessed the drastic worsening of the energy supply situation worldwide, and the accompanying flurry of frantic activities at various levels to secure alternative sources of energy to replace traditional ones that had become dear and scarce. Several truly substantial amounts of fiscal and human resources to this cause, and their determination seems to be so high in that they regard themselves as just starting in their pursuits. One type of energy that has attracted all and sundry is that from our sun, for its apparent freeness for the taking, and its cleanliness. Technologies for utilizing solar energy in diverse applications have accordingly been multiplying and are being perfected daily (Mumah et al., 2025).

Now, solar energy is being applied to air heaters, coolers, furnaces, space travel, refrigeration and air conditioning, desalination of water, generation of electricity, etc. The cost of solar energy for these different purposes do vary and depend on the geographical locations of such places as where the applications are to be made. It is therefore necessary to make a comprehensive analysis of relevant factors in deciding upon what, and on what scale a

particular application of solar energy would be beneficial. The objective of this overview, however, addresses itself particularly to the conversion of solar to electrical energy.

## **2. SOLAR TO ELECTRICAL ENERGY**

Apart from nuclear energy (and geothermal energy which is due to residual heat from radioactive decay of some rocks), all forms of energy now known ultimately derive from the sun as source. Wind, tidal, hydro, and ocean-derived energies are generated by the sun's heating of the earth and its atmosphere, as are any forms of bio-derived energies since plants depend on the sun for growth. These processes may therefore be classified as indirect generation of energy from the sun. On the other hand, solar radiation can be changed directly into electricity by making it impinge upon such materials as having the property of being excited by such radiation to initiate electron flow. This is a direct conversion of solar energy. Solar radiation can also be made to heat up fluids that are then passed through both conventional or novel turbo-generators. Despite the lack of spontaneity of transformation of radiation to electric current, here it is still reasonable to classify this group as direct when compared to the indirect class.

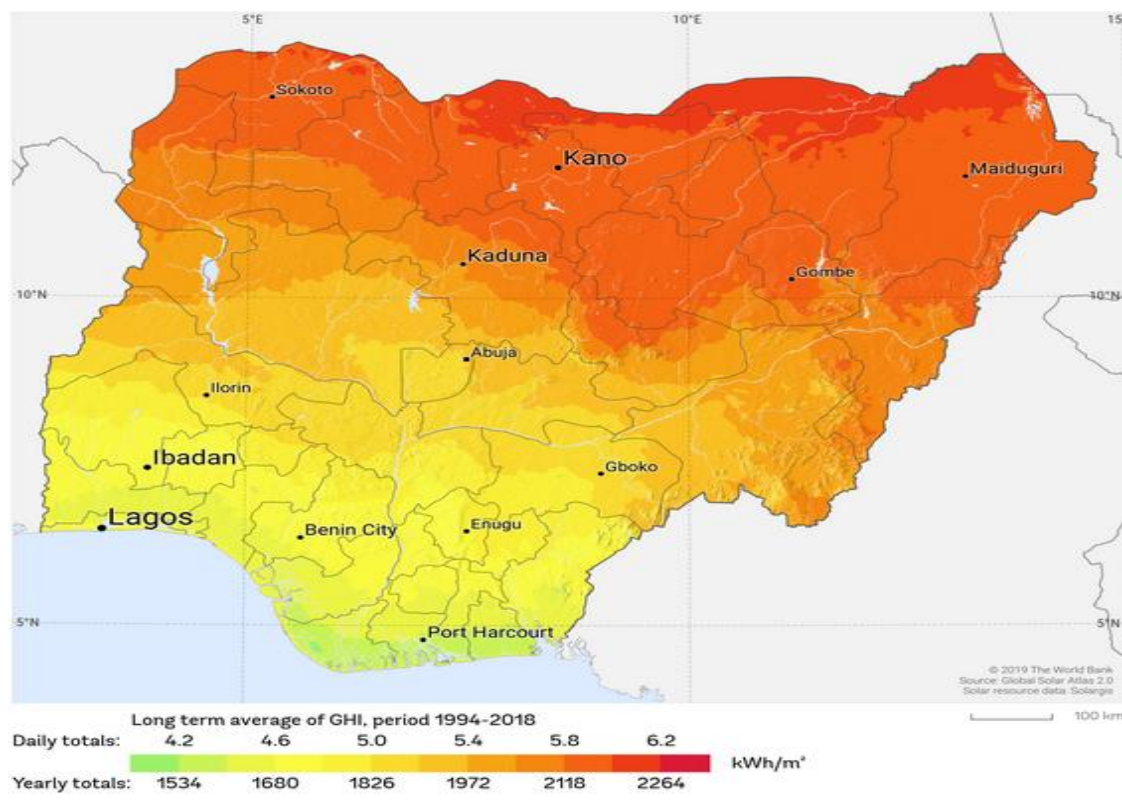
From another point of view, electricity derivation from the sun may be considered with respect to the scale of operation. Thus we may consider solar generation of electricity on the scale of conventional power stations as large-scale (above 1 MW), for neighbourhood, household or farmstead use (conventionally requiring movable generating machines) as medium-scale (100 kW to 1 MW), and for such localized uses as in charging electric car batteries for motive power and accessory functions, or for operating other small appliances, as small-scale (below 100 kW).

### **2.1. Prospects of Solar Irradiance and Solar PV in Nigeria: The Dual Mandate of Nigerian PV**

Solar Photovoltaic (PV) deployment in Nigeria represents a strategic lever for national development, driven by the dual mandate of resolving an acute energy crisis and fulfilling global decarbonization commitments. Nigeria holds the distinction of having the world's largest electricity access deficit, with the centralized national grid chronically unable to meet demand, operating production at often only one-third of its 16 GW installed capacity.

In this environment, solar PV has emerged as an economic imperative, not merely an environmental option. Decentralized solutions—Commercial & Industrial (C&I) rooftop solar, mini-grids, and Solar Home Systems (SHS)—are already cost-competitive, with lifetime Levelized Cost of Electricity (LCOE) for solar plus storage estimated at around \$0.20/kWh, significantly lower than the \$0.30/kWh to over \$0.60/kWh cost of diesel generation. This cost advantage establishes a robust business case rooted in superior reliability ([epub.wupperinst.org](http://epub.wupperinst.org))

However, realizing Nigeria's immense solar potential is constrained by systemic friction. While ambitious policy frameworks like the Energy Transition Plan (ETP) and instruments like Feed-in Tariffs (FiTs) exist to structure private investment, policy instability and contradictory fiscal measures, such as high duties on imported solar components, increase investment risk and drive up the Weighted Average Cost of Capital (WACC) (Osinowo et. al,2015)



**Figure 1.** Solar irradiation in Nigeria (SOLARBUY, 2024)

This solar resource is spread across the country. The amount of solar radiation received by each country's zones is displayed in Figure 1. The annual average of total solar radiation in Nigeria's coastal region is estimated to be between 3.5 kWh/m<sup>2</sup>/day to 5.2 kWh/m<sup>2</sup>/day (Green), whereas in the northern region it ranges between 5.2 kWh/m<sup>2</sup>/day to 7.0 kWh/m<sup>2</sup>/day (Red).

## 2.2. Direct Solar to Electrical Energy Conversion

### 2.2.1. Direct Photoconversion

Kettani (1976) has listed four feasible ways in which the photon energy of incident solar radiation may be converted directly into electricity. These ways are the photovoltaic, in which incident light initiates electron diffusion (and therefore power flow) across the junctions of doped semi-conductors; the photo emissive, in which incident light ejects electrons from the surface of suitable materials; the photo galvanic in which light incident upon a suitable solution of a dye and a reducing agent excites the agent to transfer electrons to the dye, thus reducing it chemically and in electric potential; and the photomagnetic where a suitable material at appropriate temperatures is placed in a magnetic field, and develops a potential difference upon insolation. However, only photovoltaic power generation has had extensive development and application so far.

The development of the photovoltaic source of electrical power came from the space projects of the U.S. and U.S.S.R., and today PV units find ready applications in all sizes of power requirements from proposed giant orbiting power stations to solar powered wrist watches. Although solar cells can be made from a good number of semiconductors, silicon cells are the most established in the field, perhaps because silica, the base material, is extremely abundant upon the earth. The cost of these cells has been one key problem in the competitiveness of solar-derived power with conventionally generated power (Parker & Tipton, 1978). Silicon

cells have sold for about 10-15 \$peak watt (or 1000-1500 \$m<sup>2</sup>), whereas they must cost about 10-20 cents/peak watt to compete with coal and nuclear power. Two examples of comparative cost analysis for solar cells/PV plants and other energy sources are given in Fig. 1 (Marfakis, 1976) and Table 1, the latter being more pessimistic than the former. Furthermore, solar cell utilization in power generation has been indicated as being rather too costly in energy to produce system components, so much so that unless technological advancement makes component production less energy-intensive, we might in fact be using more energy than we eventually get back from the sun through these appliances (Baron, 1978). With developments upon present technology however, solar cells are envisaged to have a 25-fold decrease in price to about 0.5 \$peak watt around 1986 (Marfakis, 1976; National Research Council, 1979). Besides this, a different manufacturing approach shows far more promise, from commercial development of amorphous-glass semiconductors. These materials ably solve both problems of high cash and manufacturing-energy costs of present-day solar cells and are envisaged to sell for about 5 cents/peak watt in the 1990s when they are more likely to make their debut (Panati, 1980). In the light of these developments, photovoltaic power production is attractive and shows long-term promise too.

(i) Large Scale (above 1 MW) PV Power Generation

**(a) Solar Power Satellites (SPS)**

Ever since 1968 when Glaser (1968) proposed a geosynchronous satellite directly intercepting solar radiation and beaming it to earth as microwaves, much work has been done to translate the idea to practice, especially in the U.S.A. where, by an ongoing \$16 million program, an experimental SPS is expected to be launched about 1990 (Dorf, 1978). The proposal is for a satellite, approximately 12 km by 4.5 km, weighing 10,000 tonnes to stay in orbit at an altitude of about 36,000 km in parallel to the earth's equatorial plane (Glaser, 1968). PV cell banks on the satellite will convert solar radiation directly to electricity and a transducer will convert this electricity to microwaves for transmission to a station on earth where a re-conversion to electricity will be effected. A single SPS could produce about 3-15 GW (i.e. about 1.5 to 7.5 times the total installed capacity of all Nigerian generating stations in 1982). The cost of the necessary research and development is estimated at about \$60 billion. A system such as that detailed above is expected to cost \$10 billion, thus generating power at about \$2/watt (NSF/NASA Solar Energy Panel, 1972). Solar energy is 15 times more available in asynchronous orbit than on earth, and some cost estimates, after taking several factors like availability, storage elimination, efficiency, and others into account, estimate that SPS power cost would be about 2-15 cents/kWh, which is cheaper than conventional (Dorf, 1978). In any case, SPS systems will also benefit from any downturn in solar cell costs.

**(b) Terrestrial Power Generation**

Rather few proposals worldwide have been made for power stations based purely on PV action, perhaps on account of cell costs, low efficiency, and area requirement. However, Japan, through its national solar energy blueprint "Project Sunshine" inaugurated in 1974, intends to produce 10 MW of PV power by 1986 and 100 MW by 1991. The United States expects to produce 5 GW by 1990 and 20 GW by 2000 A.D. (McVeigh, 1977).

**(ii) Medium Scale (100 kW to 1 MW) PV Power Generation**

There has been quite little attention so far devoted to this middle class. Most available solar plants of this grade tend to be solar thermal or other systems. However, since it is possible to use PV systems to generate power from the watt to the gigawatt range, development is only a question of time.

**(iii) Small Scale (below 100 kW) PV Power Generation**

There is a marked abundance of devices using PV power in the lower bracket of this range, but not very many in the higher bracket. Application to isolated- and hostile-environment, portable units as well as to permit virtually maintenance-free use are very common. Thus for example unmanned marine lights, automatic weather stations, portable traveler's power packs, highway telephones, fire alarms, seismographs, radio transmitters, television systems, calculators, etc. Solar power pumps and other equipment have been demonstrated even right here in Nigeria (Noli, 1981). A good number of experimental domestic units are already installed in houses around the world (especially in Europe and U.S.A.) wherein PV power from building-mounted arrays augments power from the utilities.

### **2.2.2. Solar-Thermal Power Generation**

By this approach, solar energy is made to heat up a substance or system. Electricity may then be derived from the heated substance system in a few ways. The more important ways are the direct, in which the nature of the system is such that electricity is instantaneously produced once the appropriate part of the system is insulated; the thermodynamic, in which a fluid is insulated and its expansion works a turbogenerator; and the so-called Solchem system whereby the working fluid absorbs heat from solar collector and discharges it to the heat engine by a change in chemical composition.

#### **(i) Direct Heat-Electric Conversion**

There are many ways in which heat may be converted into electricity. The more important ones are by magnetohydrodynamics in which ionised gas is passed through a magnetic field to produce electricity; thermoelectricity whereby a thermal gradient imposed between two connected dissimilar conductors (or semiconductors) produces a potential difference; and thermionic emission whereby electrons are ejected from heated metallic surfaces. Of all these methods, magnetohydrodynamics is the only one to have become a practical reality at present. Solar Magnetohydrodynamic (MHD) Power Generation.

Since definite successes have been recorded with the operation of solar furnaces up to about 3000°C and MHD systems can work well in the range 2000°C to 2500°C, it is expected that solar furnace heat will be profitably employed in ionising the gas stock for MHD systems (Bigdan, 1976). A joint U.S.-U.S.S.R. non-solar MHD plant prototype entered service in Moscow in 1977 and the Soviet Union expects to commission a 500 MW MHD plant in 1984, while the U.S. also has similar plans (Panati, 1980). Having no moving parts and operating at such high temperatures, MHD power generation is distinctly more efficient than all other present alternatives, and there is enthusiasm all around about its future widespread use.

#### **(ii) Thermodynamic Conversion**

By this process a solar-heated fluid directly works a turbo-generator to produce power. Differences in plant styles seem to arise from what best suits the intended plant output.

#### **(a) Large Scale (above 1 MW)**

This category of solar power plants seems to be enjoying much attention, perhaps because it ranks closely with conventional power plant sizes. The design pattern almost universally involves concentration of solar radiation and quite often involves tracking the sun for maximum effect. Accordingly, such plants are labelled central-receiver, solar tower, helio-electric, etc. However, some other novel approaches are also being evolved.

### **(b) Medium Scale (100 kW to 1 MW) Plants**

This category seems to be quite similar to the large-scale versions especially as regards the use of concentrating collectors, and even a tower arrangement (e.g. INTI 800). This is because of the high temperature of steam needed to generate this much power.

### **(c) Small Scale (below 100 kW) Plants**

There are also many small scale thermodynamic solar thermal plants under development. It has been shown that organic Rankine-cycle solar power plants are feasible even with flat-plate collectors and turbine inlet temperatures as low as 90°-95°C, although use of concentrators severely reduces the collector area requirement for the same power output, but is costlier (Samtel et al., 1978). Much recent work has gone into improvement upon earlier designs and these plants are expected to be widely available in a few years' time (Lorenz et al., 1973).

### **(iii) Solchem Systems**

In this system, sunlight is converted to chemical energy in a field of solar furnaces. The products are piped to a central station where energy is stored as heat-of-fusion, and heat pipe boilers provide steam for a conventional power plant. This approach has been viewed both as a direct competitor/hybrid supplement to the solar power tower concept. Sulphur trioxide (SO<sub>3</sub>) and steam-methane have figured as suitable fluids. However, the solchem method is still in its infancy (Chubb et al., 1976; Yarman, 1978).

### **Solar Towers**

Ever since the French commissioned a small-scale (60kwe) experimental plant at Odeillo in 1967, numerous large scale pilot plants have sprung up around the world and several national and international (e.g. E.E.C.) agencies have undertaken such projects (Hurwood, 1978). The U.S. was the first to embark on an actual full-scale plant, a 10 MWe unit at Barstow in the Mojave desert. Most analysts expect the cost of power from such plants to be much cheaper than from conventional plants very soon, and have made estimates that already compare favourably. For a 100 MWe unit contractors to the Energy Research and Development Agency of the U.S. estimated about \$100 million- \$170 million costs in 1976 (Eicker & Bruno, 1976), while Smith (1978) estimated \$175 million. It is certain that commercial production is going ahead (Gervais et al., 1976; Blake, 1976; Powell, 1976; Rizk & Gun, 1976; Easton et al., 1976; Pourakis et al., 1976; Smith et al., 1976).

### **Updraft Power Plants**

These are derived from a new idea that uses ordinary air as the working fluid. A giant, chimney-shaped vertical funnel is surrounded by a plastic covered area that is directly insolated. The green-house effect heats up the confined air, which, being now lighter, rises through the funnel driving a wind-turbine in the latter. West Germany seems to be in the development forefront. A two-year pilot testing is scheduled to be carried out on a plant in Spain (Aroni, 1981). Sufficient data is not yet available to permit economic assessment.

## **2.3 Indirect Solar to Electrical Energy Conversion**

The only basic difference between the “direct” and “indirect” conversion system is in the time scale of conversion, since both ultimately derive from the same source – the sun. Four important indirect sources of sun-derived electrical energy can be identified. viz; wind power, where unequal solar heating of the earth's atmosphere sets up density gradients and therefore current that are utilized in wind turbines, water power where the energy (potential or kinetic) of water is utilized in running turbo-generators:

### *2.3.1 Wind Power*

Wind power is not new. Wind utilization probably started in Egypt about five millennia ago, and many countries of the East, West, and Middle East have long traditions of the use of wind machines. Theoretically, 1% of the world's total wind energy will meet world wide energy need, but the wind's spread and highly unsteady nature set a practical limit on the extractable proportion of this energy (McVeigh, 1977). Wind-utilization technology has been advancing rapidly. Only a few years back a 500 MW wind power plant would have required 100 km<sup>2</sup> and bigger plants would require disproportionately larger land areas. Innovations like diffuser augmentation, vertical orientation, composite bearingless arrangement, blade-ducting, and many other component improvements have made wind power more attractive, and there are several experimental and working units around the world (Foreman et al., 1976; Kadlec, 1976; Spierings & Cheney, 1976).

The archetype of large-scale wind generators was the 1.25 MW Putnam machine of about 40 years ago, in Vermont, U.S.A. However, several developed nations have been fervently conducting research and development studies into large-scale utilization (Gore, 1981). The U.S. in 1980 passed a Wind Energy Systems Act which launched an 8-year, \$900 million program to develop cost-effective wind-power systems in the U.S.A. The projection is for about 30,000 large wind turbines to supply 10% of the nation's energy needs by 2000 A.D. The Scandinavian countries, U.K. and others also seem to have similar plans. By size, the whole range is in existence round the world as of now. The U.S. has a working 2 MW wind plant at Boone, Northern Carolina, besides a host of smaller units (Smith et al., 1976). Although present wind power costs (for smaller plants) is about thrice that of oil-generated power, extensive and detailed studies have indicated that with new-breed 1 MW plants the cost is likely to fall to about a third (at most) that of oil-generated power at an investment cost of about £400 to £800 per kW installed (Pelser, 1976).

One interesting application for domestic or small-community use is the hybrid wind-solar combination integrated into the architecture (Environmental Design Group, 1975). In fact, there are many imaginative ways in which the wind can supplement our traditional energy sources. Normally, electricity can be generated in winds of about 8-35 mph (3.58 to 15.65 m/sec).

### *2.3.2. Water Power*

The energy in bodies of water could be utilized in many ways. In traditional hydro-electric plants, the flow of a river is dammed to create an artificial head of fall. On the other hand, a turbo-generator is turned by waves-pumped water in a waves-electric plant, by water from a dam on a partially enclosed coastal basin filled by tides in a tidal power plant, by movement of cold water from the depths to the warm surface in an ocean-thermal-energy conversion (OTEC) plant, and by the movement of sea water down to a natural depression in a helio-hydroelectric plant.

#### **(i) Hydroelectric Power Plants**

In the context of this paper, hydroelectric power is so much an indirect form of solar energy that it does not really merit discussion. It has also been said that NEPA being unable to guarantee sufficient year-round river flow (naturally), other forms (mainly natural gas-fired) of generation are now being developed side-by-side with hydro. However, since hydroelectricity is still a major component of the Nigerian power supply, Fig. 2 and Table 2 give statistics of the power demand and supply, including hydro (Noli, 1981).

### **(ii) Tidal Power Plants**

This again is an old method of power extraction. The semi-diurnal tides of the seas are produced by the solar and lunar motions and gravitational pulls with respect to the earth. Suitable sites are partially enclosed basins with small (below 80) length to area ratios and high tidal ranges (difference between maximum and minimum heights of the tide). Several hundred suitable sites are believed to exist worldwide. If the quality (the smallness of the ratios  $L/A$  and  $L/\text{power}$  generated) of the basin is good enough, a lot of power can be generated by a tidal plant. Existing plants and those under construction (USSR, Canada, France, U.S.A., Britain, etc.) include units that produce up to 6 GW, and the investment cost has been about £600 to £800 per kW (McVeigh, 1977).

### **(iii) Waves-Power Plant**

Several technical approaches have been taken by different developers of this power source. These include buoys connected to cranks that rotate the generator blades (U.S.A.), floating air chambers that force pressurised air to work a turbine (Japan), "butterfly" rafts that force pistons to pump water to work turbines, and rocking "ducks" that drive generators (both British). Although an experimental unit off Honshu Island began producing 125 kW in 1978, the development of wave power is still in its infancy and cannot for now be assessed in detail (Panati, 1980).

### **(iv) Ocean-Thermal-Energy Conversion (OTEC) Power Plants**

These plants utilise the temperature difference of about 19–25°C (30–40°F) difference in the temperature of ocean water at the surface and at a depth of 609.6–914.4 meters (2000–3000ft). The warm surface water is made to heat a suitable working fluid to pressurised vapour which works a turbine, and is then cooled by the cold, bottom water back to liquid. Much work, worldwide, has gone into the development of OTEC technology and even the "factories-at-sea" that can be sited on and powered by OTEC plants. In the U.S., a substantial development of OTEC is taking place with a test stage of OTEC-1 now off the coast of Hawaii. 25 MW are expected by this year and 100 MW by the full-sized plant in 1984. Yearly increases are contemplated up to about 400 GW by 1996. At the same time, it has been estimated that potentially, OTEC power is roughly about a third (approximately \$1000 per kW installed) as expensive as even new nuclear power stations (Zener, 1976).

### **(v) Helio hydroelectric (HHE) Power Plants**

Wherever there are coastlines near the ocean or other large bodies of water in arid zones, a dam could be built across a valley fairly near the sea and water can be pumped behind the dam by using solar energy (the natural version of HHE relies on solar evaporation to take water back to the body of water) and the resulting difference in head utilized by a conventional hydroelectric plant. This system is still in its infancy with the Gulf of Bahrain as the first trial location (Sayigh, 1977).

#### *2.3.3. Synthetic Fuels*

These are fuels synthesized from sources other than crude oil or natural gas and used in place of them or their derivatives. They further fall into two broad subdivisions, viz. fossil-derived and bio-derived. The latter derive from living matter or their wastes.

### **(i) Fossil-derived**

The sources are mainly coal, shale, tar-sands and so-called "heavy oil" deposits. Nations with insufficient petroleum resources (U.S.A., South Africa, W. Germany, etc.) but with coal and adequate finance have been the sole developers of fossil-derived synthetic fuels. As of now,

such fuel is costlier than OPEC's petroleum, but costs are expected to tumble, especially with new methods of extraction.

### **(ii) Bio-derived**

These are mainly ethyl alcohol (ethanol), methanol, gaseous fuels (propane gas, methane from natural gas, sewer gas or gasified coal, and hydrogen), and the broad group of "oil-yielding plants." Many nations are already running vehicles on blends of petrol containing 10–20% of alcohol and efforts are on both for large scale production of methanol and even the production of vehicles to run 100% on methanol and still yield the same mileage per litre as with petroleum (the compression ratio is increased to compensate for the lower calorific value of methanol, its high octane number facilitates this). Similarly, a number of plants whose sap, latex or seed oil have been found suitable as lubricants and petroleum substitutes are being cultivated. Examples are the milk weed, the gopher plant, linseed, rapeseed, the Brazilian coibá *feralangsдорffii* tree, and the California jojoba. The alcohol fuels are the most developed in this group with Brazil as the leading adopter, but methane production is also showing promise. Methane production by anaerobic fermentation of algae has also been suggested (Seifert et al., 1973).

#### *2.3.4. Indirect Photochemical Systems*

Some novel approaches have been suggested for indirect solar energy conversion. The more important ones are photolysis wherein free radicals are formed by photon excitation, and photoionization in which light energy initiates ionization. The application of these processes to nitrosyl chloride and caesium respectively are believed to be potentially viable solar energy conversion methods.

**Table 2.1.** Solar Energy prospects Estimates (Baron, 1978)

S/No	Category	Prospects and Estimates
1	Fossil/Nuclear plant	0.6-0.8 actual power factor and Cost \$1100/kwe
2	PV system	Feasible now in isolated plants in institution, hotels, apartment houses, office buildings, amusement parks, etc.
3	Wind and biomass OTEC	Were feasible and obtainable Will be feasible at the turn of the century

## **3. MATERIAL AND METHOD**

### **3.1. The Nigerian Resource Base**

Lying between the latitudes 4° and 14° of the equator, with an entire boundary washed by the Atlantic Ocean and vegetation varying from rain forest to sub-Sahara Desert conditions, it is clear that in the light of all the foregoing geographical requirements for the diverse ways of profitably harnessing solar energy, Nigeria is particularly blessed. She has a land area of almost a million square kilometres and is distant by about 30 km (Lagos/Badagry) to 140 km (Oron coast) from 2 km deep ocean.

### **3.2. Demand and Supply Trends in Nigeria's Power Sector**

Nigeria's electricity sector, dominated by existing power plants (primarily gas-fired thermal plants accounting for approximately 80% of generation, with hydropower contributing the remainder), continues to face a persistent supply-demand imbalance. Installed capacity exceeds 13,000 MW, but actual generation is constrained by gas shortages, infrastructure limitations, and transmission losses, typically operating at 30-40% of potential. Demand has grown steadily

due to population increases and economic activity, while supply has shown modest gains but remains insufficient, leading to widespread reliance on self-generation.

Table 3.1 below summarizes yearly trends for electricity supply (generation) and demand (consumption) from 2019 to 2024, based on data from the International Energy Agency (IEA), Enerdata, Statista, and Our World in Data. Values are in terawatt hours (TWh). Note that 2024 data reflect preliminary estimates as of late 2025.

Table 3.1: The Demand and Supply Trend and the Existing Power Plants Respectively

Year	Supply (Generation, TWh)	Demand (Consumption, TWh)	Gap (Demand - Supply, TWh)	Status
2019	32.0	30.0	-2.0	Supply exceeded demand slightly due to exports and losses; per capita consumption ~145 kWh.
2020	28.0	26.0	-2.0	COVID-19 reduced demand; generation dipped amid economic contraction.
2021	31.0	28.0	-3.0	Recovery in demand; supply grew modestly via improved gas utilization.
2022	35.0	32.0	-3.0	Peak supply growth; residential demand dominant (~61% of total).
2023	40.7	40.0	-0.7	Strong demand surge; generation hit record high, but access remains at ~60%.
2024	38.0	33.0	+5.0	Demand dipped 3% amid economic slowdown; supply constrained by outages. Per capita ~140 kWh.

This table above illustrates an average annual supply growth of ~3.7% versus demand growth of ~2.7%, yet the structural gap persists due to inefficiencies (e.g., 20-30% transmission losses). Projections for 2025 suggest demand rising to ~41 TWh, necessitating urgent investments in existing plants' maintenance and gas supply to bridge the deficit.

Nigeria is also largely a single-resource (oil) country, whose financial fortunes depend on the market price of crude petroleum. The last budget for 2024 shared an expected oil-sourced revenue. She currently produces crude petroleum at the rate of 1.4 million barrels per day and crude reserves are projected to last at least 25 years and probably more. She has even more natural gas and coal. As a proper start for systematic energy research, millions was voted, of which some amount has recently been disbursed towards nuclear and solar energy research.

The required research and development personnel are believed to exist throughout the research institutes, universities and polytechnics of the land, for the purposes of creation, adaptation or commercialization of solar energy technology.

### **3.3. Nigeria's Options for Solar-derived Electricity**

It is clear that for any nation, a solution of the energy problem must be in the form of using an energy mix. Although the well sung energy crisis has been simply dissected into two—overconsumption in the developed world and underconsumption in the third world, yet it is clear that Nigeria does have an energy crisis with peculiarities of its own. The supply of power is yet very inadequate. Home oil consumption is growing (the 4th national development plan estimates it to be 440,000 barrels/day in 1985) and it has even suggested that by 1990, Nigeria may be consuming about 50% of her oil output. By that time too, if large reserves are not discovered, the resulting revenue downturn would have serious effects on the nation's development. In short, the country increasingly needs the oil revenue to finance development, but she also needs increasingly more of the oil for her own use, and in any case has progressively less to draw upon. Also, Nigeria has borrowed for the past 17 years to finance her electric power development, so it is not as if we had so much money to provide energy.

Again, it has been observed that there is a 20:1 economic advantage in processing our crude to petrochemical end-products rather than selling as mined. At the same time it is well known that the developed nations already see the third world as a rich market for all grades of solar devices. In the light of these facts, it is essential that alternative energy sources be developed quickly both to directly improve the quality of life, especially in the rural areas, and also to take the heat off our dwindling fossil reserves, and to help us prevent, wherever possible, needless waste of money on importation of appliances and technology that we can wholly or partially supply. We may consider the solar-electric conversion methods reviewed to see what the country can do about them.

#### **3.3.1. Photovoltaic Conversion**

If the expectations of cheap solar cells materialise, then large-scale PV power production will be desirable. For now, medium- and small-scale units are very useful for domestic, institutional and rural-community needs in many forms. Solar cell research, product development and integrated architectural applications suggest themselves. Solar power satellites cannot be considered as we have neither the money nor the technology.

#### **3.3.2. Solar Thermal**

The solar tower system can be kept in mind for the very highly insulated parts (e.g. Sokoto State) of Nigeria. The updraft system is very attractive for an even wider area of northern Nigeria, and it seems most desirable to develop it. Small and medium size plants can be of immediate use but it is suggested that a careful selection be made to ensure that in their class, other approaches are not in fact better. Magnetohydrodynamics also seems, at least for commercial purposes, to be beyond our grip at the moment, considering the required finance and technology.

The Solchem system is not really complicated and since it is deemed competitive with solar thermal, it should not be ignored for adoption and development.

#### **3.3.3. Wind Power**

There is great potential in wind power development, especially along the coastline, and for smaller units all over the rest of the country. This with direct-solar, is an energy source that can help much in the rapid transformation of our rural and isolated areas.

#### **3.3.4. Water Power (Hydro)**

River Niger has been dammed in many places, and the Benue is now being similarly dammed. We shall soon be left with the ocean only, if we want water power. It appears that if non-hydro

water resources are considered, more serious attention should be given to waves and tides than OTEC and HHE on account of the larger sizes the former plants tend to generate. However, it is possible that economical OTEC plants may soon be on the market.

### **3.3.5. Synfuels**

It is clear that sooner or later our petroleum stock will be finished. It is therefore not out of place for us to start serious work on alternative fuels research and use. If synfuels (especially bio-derived ones) are available cheaply in remote places, we save on premium petroleum, transportation and distribution costs, etc., by using them instead.

### **3.4. Overview of Renewable Energy Initiatives in Nigeria**

Nigeria, facing a significant electricity access gap affecting over 85 million people, has prioritized renewable energy to enhance energy security, reduce emissions, and support economic development. With an installed capacity dominated by gas-fired plants, the country aims to leverage its abundant renewable resources—estimated at over 68,000 MW from solar, wind, biomass, and hydro sources—to meet growing demand and achieve sustainable goals. Key frameworks include the Nigeria Energy Transition Plan (ETP), which targets net-zero emissions by 2060 across sectors such as power, cooking, transport, industry, and oil and gas. This plan emphasizes renewables-backed electrification, with solar playing a pivotal role in replacing gas as a transition fuel, aiming for nearly 100% emissions reduction in the power sector.

### **3.5. Major Policies and Frameworks**

Nigeria's renewable energy landscape is guided by several policies and agencies:

- National Renewable Energy and Energy Efficiency Policy (NREEEP, 2015): Establishes targets for renewable integration, including 23% renewable energy in the total energy mix by 2025 and 36% by 2030.
- Nigeria Electrification Project (NEP): Focuses on off-grid solutions, having established 125 mini-grids and distributed over a million solar home systems.
- Rural Electrification Agency (REA): Implements decentralized renewable projects, including mini-grids, solar home systems, and productive use programs, impacting over 7.8 million people and supporting 11,400 micro, small, and medium enterprises (MSMEs).
- Energy Transition Plan (ETP): Projects a total installed capacity of 277 GW by 2060, with renewables driving decarbonization in cooking (via electric stoves and biogas), transport (electric vehicles), and industry (zero-emission fuels).

### **3.6. Key Initiatives and Projects**

Table 3.2 shows Prominent Renewable Energy Initiatives, Including Objectives, Scope, And Achievements as of Late 2025. ([energytransition.gov.ng](http://energytransition.gov.ng)).

## **4. RESULTS, CHALLENGES AND OPPORTUNITIES**

- a. Firstly, the governments and private industries of this country need to know that much more money than recently voted for energy research and development is needed, on a continuing basis, for the good of all.
- b. A centralised, single although multifaceted government national energy policy is necessary. The taking of our energy inventory, assessment of our position in a world context and projections for our future safety and prosperity shall be reflected in such a policy. It is desirable that all plans, research and development and other contracts have set and monitored objectives.

- c. Joint development, both with technically advanced partners on one hand, and our O.A.U. and ECOWAS brothers on the other should be preferred to the "perpetual purchaser" role, as much as possible.
- d. Eight new, small and medium scale, state-of-the-art solar products exist that can be bought and utilized. Such applications, with concerted local or joint research and development especially for photovoltaic, solar thermal and wind energies are perhaps most relevant.

**Table 3.2** Renewable Energy Initiatives, Objectives, and Some Achievements

Initiative	Description	Key Objectives and Scope	Achievements/Status
Distributed Access through Renewable Energy Scale-up (DARES)	A World Bank-financed project (\$750 million IDA credit, plus over \$1.3 billion in additional funding) to deploy distributed renewables like standalone solar and mini-grids.	Provide new or improved electricity access to 17.5 million Nigerians; replace 280,000 polluting generators; prioritize gender inclusion and MSMEs.	Builds on NEP; expected to benefit 237,000 MSMEs with clean power; ongoing implementation since 2023.
Rural Electrification Agency (REA) Programs	Includes Distributed Energy (DE) program, National Public Sector Solarisation Initiative (NPSSI), and African Mini-Grid Program; focuses on private sector-led mini-grids and solar systems.	Address rural electrification gap in 700,000 communities; tie energy to productive uses in agriculture and businesses; deploy 94 MW of PV capacity.	Over 1.1 million connections; \$400 million in grants disbursed, with \$900 million in pipeline; examples include 250 kW and 200 kW mini-grids.
Katsina Wind Farm	A 10 MW pilot wind project in northern Nigeria.	Demonstrate wind energy viability; contribute to diversified renewable mix.	Operational since 2020; part of broader wind pilots.
Stand-Alone Solar for Productive Use	REA-led program providing solar systems for off-grid areas.	Enhance access for dispersed settlements; support livelihoods and MSMEs.	Integrated into NEP; over a million systems distributed.
Investments to End Poverty Initiative	Government-led effort to expand renewable access as a poverty reduction tool.	Reduce poverty through reliable electricity; target 100 million Nigerians with modern energy services.	Aligns with ETP; projected to create 340,000 jobs by 2030 and 840,000 by 2060.

## 5. CONCLUSION

Despite progress, barriers persist, including financing gaps, policy fragmentation, high costs, and skills shortages. Opportunities lie in untapped resources like biomass and geothermal, with renewables potentially meeting 60% of demand by 2050 if plans are executed. International partnerships, such as with the World Bank and SEforAll, are crucial for scaling investments. In summary, Nigeria's renewable initiatives represent a strategic shift towards sustainability, with a focus on decentralized solutions to bridge the energy access divide while aligning with global climate commitments. Continued investment and policy coherence will be essential for realizing these goals.

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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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## DYNAMIC STABILITY IMPROVEMENT OF HYBRID RENEWABLE ENERGY SYSTEMS USING ENHANCED FOPID CONTROLLERS

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### ABSTRACT

*The rising global demand for electrical power has increased the adoption of Hybrid Renewable Energy Systems (HRES) as a sustainable supply alternative. However, integrating renewable sources into microgrids introduces frequency and voltage stability challenges due to nonlinear dynamics and generation intermittency. This study develops a HRES-based microgrid model and employs a Fractional Order PID (FOPID) controller whose parameters are optimized using the Kepler Optimization Algorithm (KOA) and Particle Swarm Optimization (PSO). System performance is assessed using overshoot, undershoot, settling time, and rise time metrics. Results show that KOA-FOPID offers superior dynamic response compared with PSO-FOPID. For frequency stability, KOA-FOPID achieves shorter settling time (3.62 s compared with 4.79 s) and rise time (13.533 s compared with 15.257 s), with comparable undershoot. For voltage stability, KOA-FOPID further improves performance by reducing overshoot (65.83% compared with 84.26%) and undershoot (1.526 compared with 1.885), and by achieving faster settling (3.23 s compared with 4.37 s) and rise times (120.06 s compared with 131.43 s). These findings establish KOA-FOPID as an effective and robust framework for enhancing the stability and resilience of HRES-based microgrids.*

### 1.0 INTRODUCTION

The fabric of modern civilization is intricately woven around the foundational element of energy (Mao et al., 2024). Energy is not only the driving force behind industrial growth and technological advancement but also an essential requirement for sustaining human life, powering communication, transportation, healthcare, and domestic needs. Universally, it is acknowledged that sustainable human development is impossible without a reliable energy supply (Solomon et al., 2024). Thus, energy statistical studies have shown that between 2005

and 2030, the world's energy consumption is expected to rise by nearly 55 percent (Bigerna et al., 2021).

In electricity generation, the past decade has recorded a global surge in renewable energy integration, with solar and wind power emerging as the fastest-growing and most widely deployed technologies (Sabo et al., 2024). Forecasts from the International Energy Agency (IEA) anticipate that by 2030, renewable energy will supply nearly 46% of global electricity, with solar photovoltaic (PV) and wind jointly accounting for around 30% reflecting their dominant share in the rapid expansion of clean energy infrastructure (IEA, 2024). Hence, to harness these renewable potentials in improving energy access, reliability and sustainability, various approaches like microgrids, smart grids, hybrid renewable systems, and off-grid are adopted depending on technical, economic, and geographic considerations (Lund et al., 2015). Microgrids are considered economical and viable solution in addressing epileptic power challenges especially in places where there is difficulty in reaching the national or regional power systems (Sabo et al., 2024). It is a research centric innovation requiring more studies in achieving the desired stability (Ali et al., 2023). In harnessing microgrid potentials, harmful effects of energy sources on the ecosystem informs the decision of exploring clean energy sources of energy like wind power generation (WPG), solar power generation (SPG) or a combination of both generation system in forming a reliable centralized power grid. Hence, the design of hybrid renewable energy system (HRES) requires other alternate sources of energy like geothermal plants and biomass plants which can participate during short term power fluctuation (Shankar et al., 2015).

In this study, the dynamic stability of Hybrid Renewable Energy Systems (HRES) was enhanced by improving both frequency and voltage stability in a single area HRES-based microgrid using optimized FOPID controllers. The system was modeled in MATLAB, while FOPID parameter optimization was performed using the Kepler Optimization Algorithm (KOA) and Particle Swarm Optimization (PSO).

To this end, the following objectives were defined to guide the design of an enhanced FOPID controller for improving the dynamic stability of the HRES-based microgrid system:

- To model a HRES-based Microgrid incorporating renewable energy sources and their dynamic interactions.
- To design a Fractional-Order PID (FOPID) controller capable of enhancing both frequency and voltage stability under varying operating conditions.
- To optimize the FOPID controller parameters using the Kepler Optimization Algorithm (KOA) and Particle Swarm Optimization (PSO).
- To evaluate and compare the performance of KOA-FOPID and PSO-FOPID in terms of overshoot, undershoot, settling time, rise time and establish the more effective optimization technique for robust stability control.

## **2. SYSTEM DESCRIPTION**

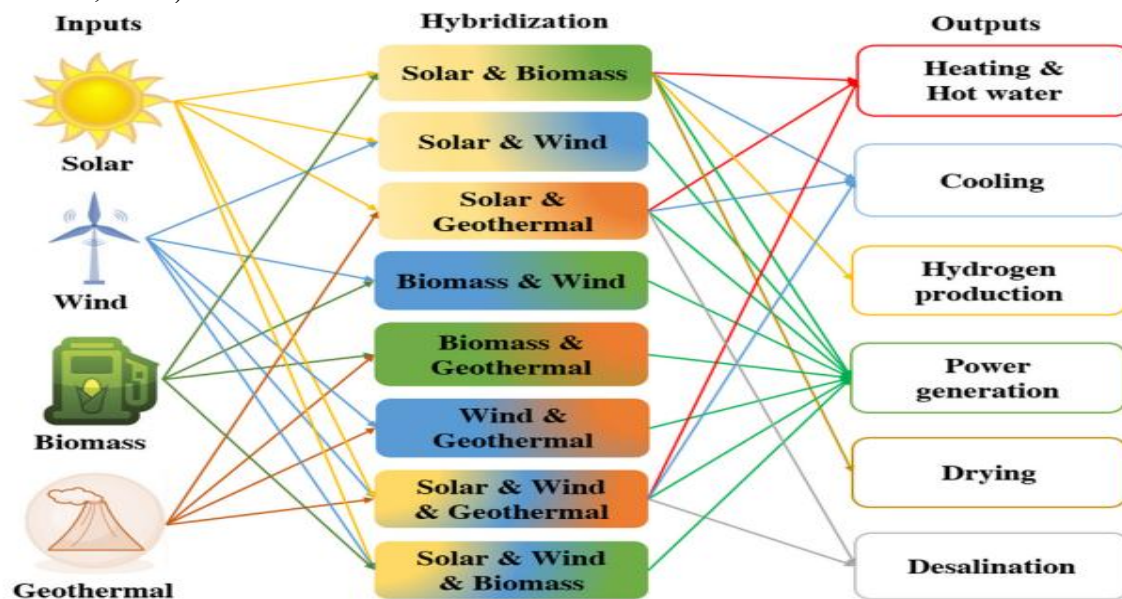
This section provides a concise overview of the theoretical foundations and essential concepts relevant to the present study, serving as the basis for subsequent modeling, controller design, and optimization analysis.

### **2.1 Hybrid Renewable Energy System (HRES)**

Microgrids and hybrid renewable energy systems play a crucial role in today's energy transition. They enable local power generation and distribution, reducing dependence on large centralized infrastructures, can operate independently or connected to a grid, and can provide

backup power, thus increasing system resilience (Pranav et al., 2017), (Sabo et al., 2024). However, system of analysis of HRES is highly difficult and must be extensively examined due to the various generating systems. The optimization goals of renewable-based hybrid systems are to achieve optimal operating conditions and economic evaluation and optimize their performance to the point where all their physical and technical constraints are satisfied (Thirunavukkarasu et al., 2023)

Recently, the systems combining solar energy and the other renewable sources like biomass or geothermal energy is gaining popularity due to the fluctuation of solar irradiance. The road map toward HRE utilization for electrification, space heating and other application are as shown Figure 1 which presents the route towards Hybrid Renewable Energy System utilization (Guo et al., 2018).



**Figure 1.** Hybrid Renewable Energy System (Guo et al., 2018)

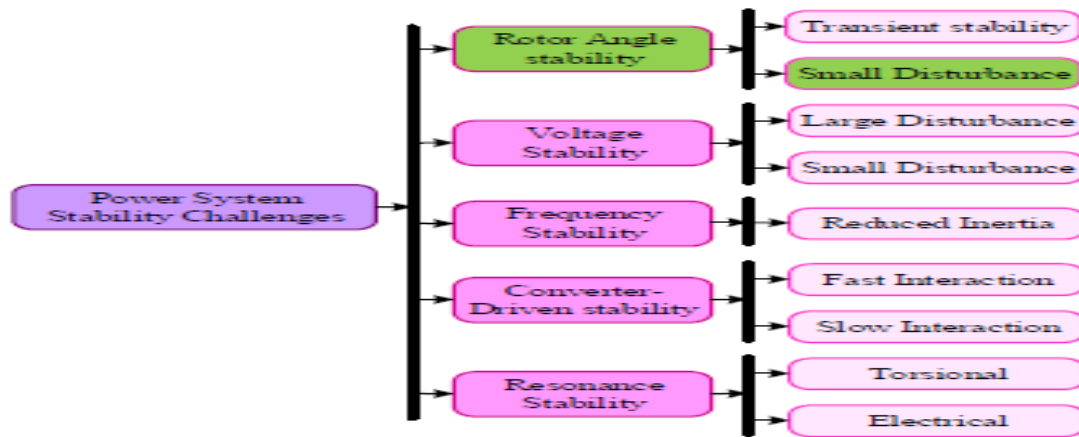
## 2.2 Power System Stability

Power System Stability refers to the ability of an electrical power system to return to its initial steady state following a disturbance. In traditional power systems based on synchronous machines, stability encompasses rotor angle, voltage, and frequency (Sabo et al., 2024).

### 2.2.2 Power System Stability Challenges

The increasing presence of distributed generations based on renewable energy sources in power generation has introduced novel forms of power system instabilities (Aderibigbe et al., 2022).

Recent studies have identified resonance stability and converter driven stability as emerging categories of power system stability as shown in Figure 2 (Hatziaargyriou et al., 2020). Voltage Stability results from variations in voltage at the generating terminals of a given power system. One of its major causes is change in reactive power at the load center and requires a well-designed control mechanism for proper a proper voltage regulation (Diyari et al., 2025). With respect to renewable solutions like wind and PV plants, an efficient voltage stability mechanism, particularly at the point of common coupling (PCC), is imperative to prevent wind and PV plants from disconnecting from the power grid (Sabo et al., 2024).

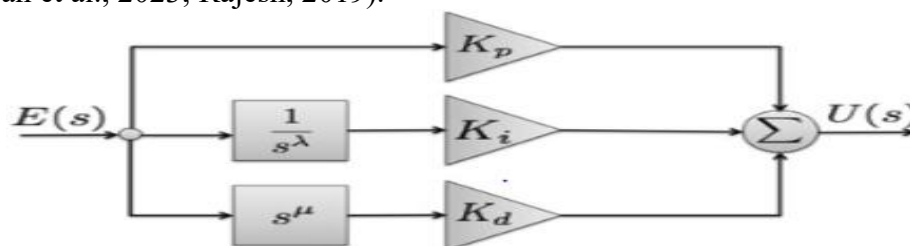


**Figure 2** Power System Stability Challenges (Hatziaargyriou et al., 2020)

Frequency Stability is a power system stability area that ensures that a stable frequency within an acceptable range in the power network is achieved. The integration of renewable power solutions into the grid makes it interconnected but impacts the stability of the power systems. Thus, maintaining the frequency and tie-line power to the schedule value is critical as changes in real power in terms of variable load demand easily affects Frequency (Sabo et al., 2022).

### 2.3 FOPID Power System Stability Controller

FOPID controller is the expansion of the conventional PID controller based on fractional calculus. The orders of integration and differentiation are respectively  $\lambda$  and  $\mu$  (both positive real numbers, not necessarily integers) (Diyari et al., 2025). In recent years, the fractional-order proportional–integral–derivative (FOPID) controller, depicted in Figure 3, has been increasingly adopted as a substitute for the conventional PID controller owing to its advantages (Murugesan et al., 2023; Rajesh, 2019).



**Figure 3.** FOPID Block Diagram (Murugesan et al., 2023)

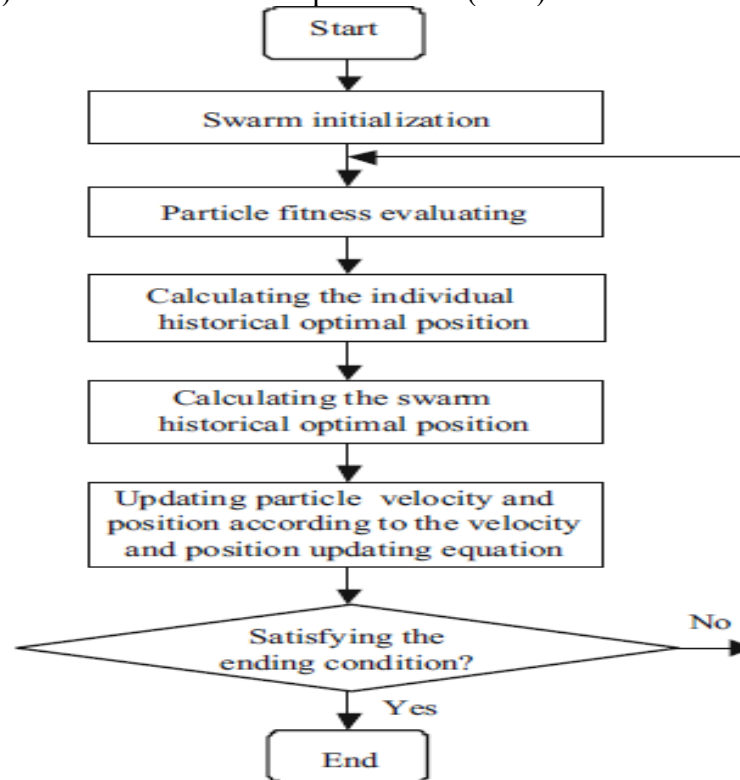
### 2.4 Metaheuristic optimizers

Metaheuristic algorithms are also applied to solve global optimization problems when the problem structure is not known. For exploring the search space, these algorithms are generally based on the use of random variables, which make it possible to follow non-deterministic paths to reach a solution (Chicco & Mazza, 2020)

In the power and energy domain, metaheuristic optimization is widely used to solve many problems referring to operation, planning, control, forecasting, reliability, security, and demand management. A set of typical problems that are solved with metaheuristic optimization including unit commitment, economic dispatch, optimal power flow, distribution system reconfiguration, power system planning, distribution system planning, load forecasting, and maintenance scheduling (Chicco & Mazza, 2020).

### 2.4.1 PSO

Particle swarm optimization (PSO) algorithm is a stochastic optimization technique based on swarm which simulates animal's social behavior, including insects, herds, birds and fishes. These swarms conform a cooperative way to find food, and each member in the swarms keeps changing the search pattern according to the learning experiences of its own and other members (Wang et al., 2018). The Particle Swarm Optimization (PSO) Flow chart is shown in Figure 4.



**Figure 4.** Particle swarm optimization (PSO) Flow chart (Wang et al., 2018)

### 2.4.2 Kepler optimization algorithm (KOA)

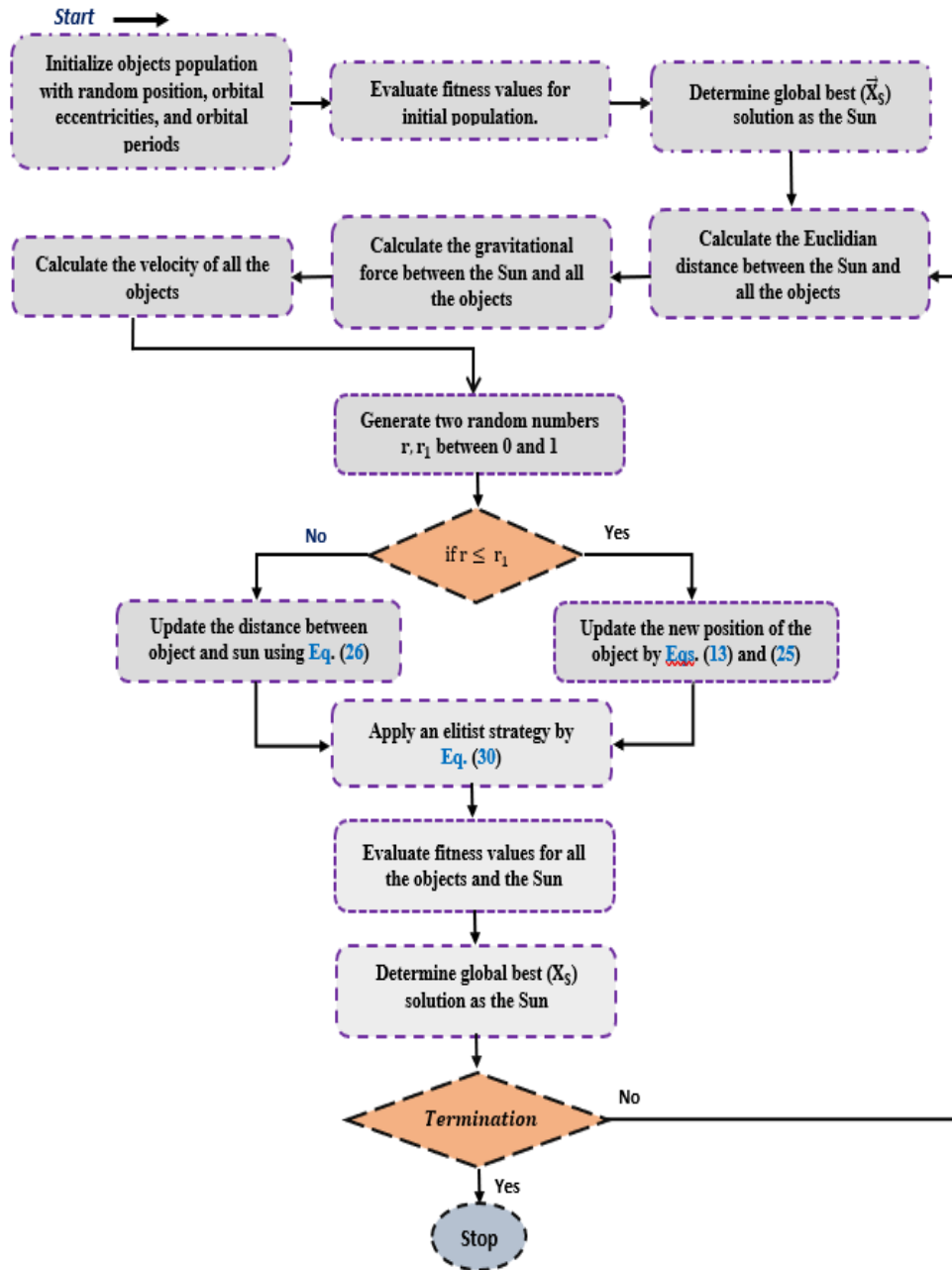
Kepler Optimization Algorithm (KOA) is physics-based metaheuristic algorithm inspired by Kepler's laws of planetary motion to predict the position and velocity of planets at any given time (Abdel-Basset et al., 2023). KOA allows for a more effective exploration and exploitation of the search space because the candidate solutions (planets) exhibit different situations from the Sun at different times. Four challengeable benchmarks, namely CEC 2014, CEC 2017, CEC 2020, and CEC2022, and eight constrained engineering design problems. Thus, the Kepler Optimization Algorithm Flow chart is presented in Figure 5.

## 3. MICROGRID MODELLING AND OPTIMISATION

The Microgrid System adopted for this study is as illustrated by the two-area Hybrid Renewable Energy System (HRES). The system integrates multiple renewable sources, including photovoltaic (PV) power plants, hydro power plants, combined biomass heat and power units, and wind power plants.

### 3.1 Hybrid Renewable Energy System (HRES) Modelling

The Hybrid Renewable Energy System (HRES) is modelled in MATLAB Simulink. It consists of Solar PV Power, Hydro Power Plant, Combined Biomass Heat and Power (CBHP) Unit, Wind Power Plant. The AVR and LFC loop Model are also considered to enable the frequency and voltage stability of the interconnected power system.



**Figure 5.** Kepler Optimization Algorithm (Abdel-Basset et al., 2023)

### 3.1.1 Solar Photo Voltaic Power System

The PV unit converts the solar radiation into electricity. The modelling of the PV power plant is as represented in Equation 1 (Fayek & Rusu, 2022).

$$G_{PV} = \left( \frac{\Delta P_{PV}}{\Delta I} \right) = \left( \frac{1}{1 + sT_{PV}} \right) \quad (1)$$

Where;  $T_{PV}$  is the Photo Voltaic Time constant of the

### 3.1.2 Hydro Power Plant

The unit converts wastewater into electric energy. It consists of transient droop compensation hydro governor and hydro turbine. The transfer function equation for the hydro power plant is represented in Equation 2 (Ali et al., 2023; Fayek & Rusu, 2022).

$$G_{CBHP} = \left( \frac{K_{mg}}{1+sT_{hg}} \right) \left( \frac{1+sT_{rs}}{1+sT_{rh}} \right) \left( \frac{1-sT_{ht}}{1+0.5sT_{ht}} \right) \quad (2)$$

Where;  $K_{mg}$  is MHT participation factor,  $T_{hg}$  is the THG transient droop,  $T_{rs}$  delay Time of the Governor system,  $T_{rh}$  is reset Time and the Turbine Delay Time is  $T_{ht}$ .

### 3.1.3 Combined Biomass Heat and Power (CBHP) Unit

The Combined Biomass Heat and Power unit converts solid waste into electricity. The system includes a steam turbine, reheater, and speed governor. The mathematic modelling is as represented in Equation 3 (Fayek & Rusu, 2022).

$$G_{CBHP} = \left( \frac{K_{BC}}{1+sT_{BC}} \right) \left( \frac{1+sK_R T_R}{1+sT_R} \right) \left( \frac{1}{1+sT_{BCT}} \right) \quad (3)$$

Where;  $K_{bc}$  is the Combined Biomass Heat and Power participation factor, speed governor time constant is  $T_{BC}$ , Turbine Gain Value is  $K_R$ ,  $T_R$  is the turbine time constant while the CBHP reheater time constant is  $T_{BCT}$ .

### 3.1.4 Wind Power System

The wind power generating unit consists of data fit pitch response and the hydraulic pitch actuator unit. The mathematically described in Equation 4 (Ali et al., 2023).

$$G_W(s) = \left( \frac{K_{w1}K_{w1}(1+sT_{w1s})}{(1+T_{w2s})(s^2+2s+1)} \right) \quad (4)$$

Where; wind plant gain constants are  $K_{w1}$  and  $K_{w2}$  and wind turbine time constant are  $T_{w1}$  and  $T_{w2}$  respectively.

## 3.2 Modelling of FOPID Controller

The FOPID controller which is an advance form of PID controller with two additional parameters of fractional order integrator order ( $\lambda$ ) and fractional derivative order ( $\mu$ ) make its performance better and switching parameters make its more valuables. Thus, fractional-order dynamic model is as represented in Equation 5 (Chen et al., 2020).

$$G(s) = K_P + K_I S^{-\lambda} + K_D S^\mu \quad (5)$$

Where;  $K_P$  is the Proportional Gain, the integral gain is  $K_I$ ,  $K_D$  is the Derivative Gain, the order of integration is  $\lambda$  and the order of integration order is  $\mu$ .

## 3.3 Optimization of FOPID For Optimal Performance

In carrying out the optimization for AVR-LFC controller, Kepler optimization algorithm (KOA) and Particle Swarm Optimizer (PSO) are proposed. The objective function of the optimization, error criteria and the constraint are presented in this subsection.

### 3.3.1 Optimization Objective Function Evaluation

The objective function (J) is evaluated to ensure that error (e) is minimized. Optimization is formulated based on minimizing the cost function using Integral time absolute error (ITAE) (G. Shankar et al., 2015), (Mohamed et al., 2023). The evaluation of the Objective Function is as expressed in Equation 6.

$$J_{ITAE} = \int_0^\infty t [ |\Delta f| + |\Delta V_t| ] dt \quad (6)$$

Where the Error cost function of the objective function is denoted as  $J_{ITAE}$

### 3.3.2 FOPID Optimization Constraint

The optimization's constraint for the FOPID Controller is defined by the lower and higher bounds of the optimized parameters. In this case,  $(K_p^{min}, K_i^{min}, K_d^{min}, \lambda^{min}$  and  $\mu^{min})$  are the lower bounds of the proportional and integral parameters while  $(K_p^{max}, K_i^{max}, K_d^{max}, \lambda^{max}$  and  $\mu^{max})$  represent the upper bound accordingly.

### 3.3.3 Parameter Settings

In optimizing the performance of the of PID and FOPID controller, the optimization parameters proposed are as presented in Table 1.

**Table 1.** FOPID Parameter Settings for the optimization technique

Parameter	Setting
Number of variables	5
Variables	$K_p, K_I, K_D, \lambda$ and $\mu$
Population size	200
Iterations	100
Lower boundary	[0, 0,0,0,0]
Upper boundary	[20, 20,20,1,1]

## 4. RESULT AND DISCUSSION

At the conclusion of the Hybrid Renewable Energy System (HRES) modeling and the optimization of its FOPID controllers for the two-area microgrid power system, the key findings were systematically analyzed. The optimization outcomes, along with the corresponding voltage and frequency stability profiles, were obtained and evaluated. Furthermore, the performance indices of the designed controllers were assessed based on the Kepler Optimization Algorithm (KOA) and Particle Swarm Optimization (PSO), providing a clear basis for comparing their effectiveness. These results form the foundation for the subsequent discussion and performance evaluation of the proposed control schemes.

### 4.1 Optimisation Parameters

The FOPID controller parameters were optimized using the Kepler Optimization Algorithm (KOA) and subsequently evaluated through Particle Swarm Optimization (PSO) for comparative analysis. To ensure optimal dynamic performance of the hybrid renewable energy system, the Integral of Time Absolute Error (ITAE) criterion was employed as the performance index in this study.

#### 4.1.1 Microgrid FOPID Optimisation Parameters

Table 2 presents the optimized parameters of the Fractional Order PID (FOPID) controller for Area 1 of the Hybrid Renewable Energy System (HRES)-based microgrid. The optimization process was performed using the Kepler Optimization Algorithm (KOA) with the objective of improving both frequency and voltage stability, which represent critical performance indices in microgrid operation.

**Table 2.** KOA-FOPID Parameters

FOPID Parameter	STABILITY	
	Frequency	Voltage
$K_p$	3.22	2.47
$K_I$	6.51	9.34
$K_D$	10	1.00
$\lambda$	0.74	0.95
$\mu$	0.28	0.86

Table 3 presents the Fractional Order PID (FOPID) controller parameters for the HRES-based microgrid, optimized using Particle Swarm Optimization (PSO).

**Table 3. PSO-FOPID Parameters (AREA 1)**

FOPID Parameter	STABILITY	
	Frequency	Voltage
$K_p$	4.91	2.15
$K_i$	9.32	5.11
$K_d$	6.85	1.00
$\lambda$	0.87	0.58
$\mu$	0.47	0.96

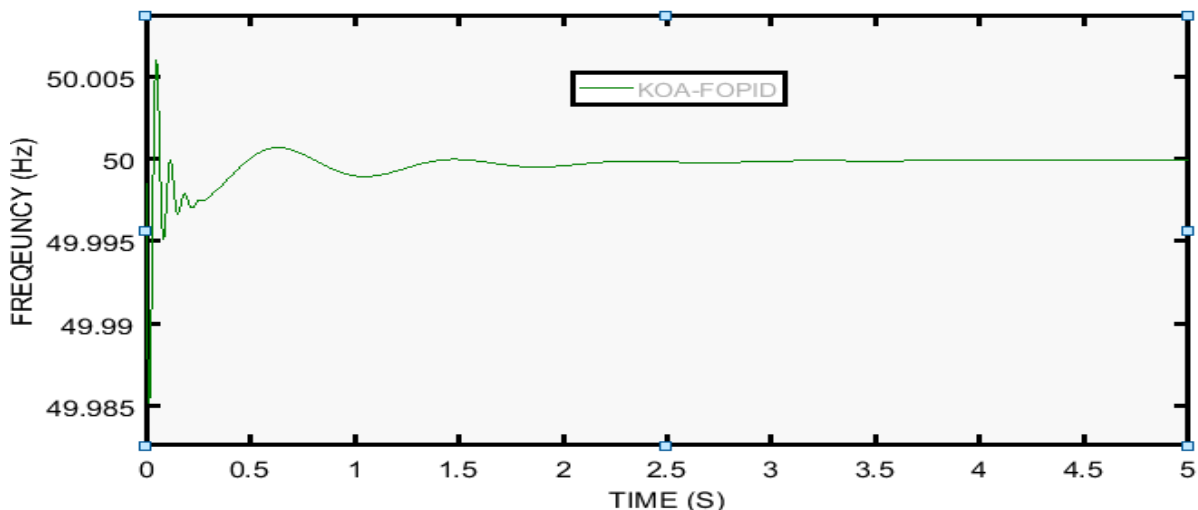
### 4.2 Stability Profiles

After optimizing the parameters of the Fractional Order PID (FOPID) using Kepler Optimization Algorithm (KOA) and Particle Swarm Optimization (PSO). The designed controllers were used for voltage and Stability control in the power system. The profiles for both Area 1 and Area 2 of the HRES-based microgrid are presented in this subsection.

#### 4.2.1 HRES-Based Microgrid Frequency Stability Profile

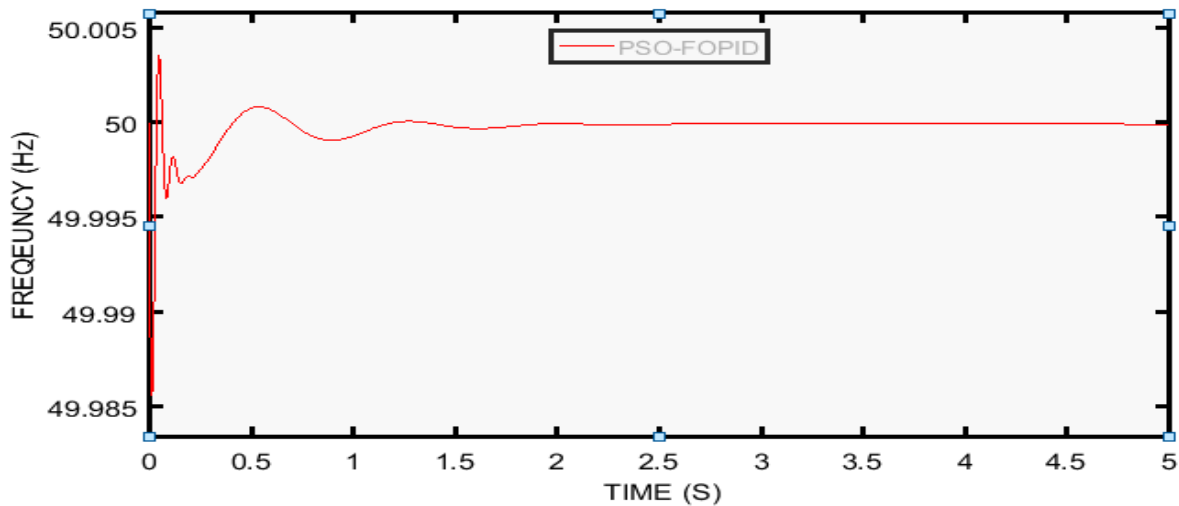
Using the designed KOA and PSO-based FOPID controllers, the frequency stability profiles of the HRES-based microgrid were obtained. The results are presented in Figure 6, Figure 7 and Figure 10 corresponding to the KOA-FOPID frequency controller, PSO-FOPID frequency controller, and the Combined Frequency Response, respectively.

In Figure 6, the frequency response illustrates the system’s ability to stabilize after an initial fluctuation caused by a load disturbance. The KOA-FOPID controller exhibits strong performance, effectively suppressing oscillations and restoring stability. At the onset, the system experiences a slight frequency deviation, oscillating between approximately 49.985 Hz and 50.005 Hz. Within 3.62 seconds, the frequency settles very close to the nominal 50 Hz.



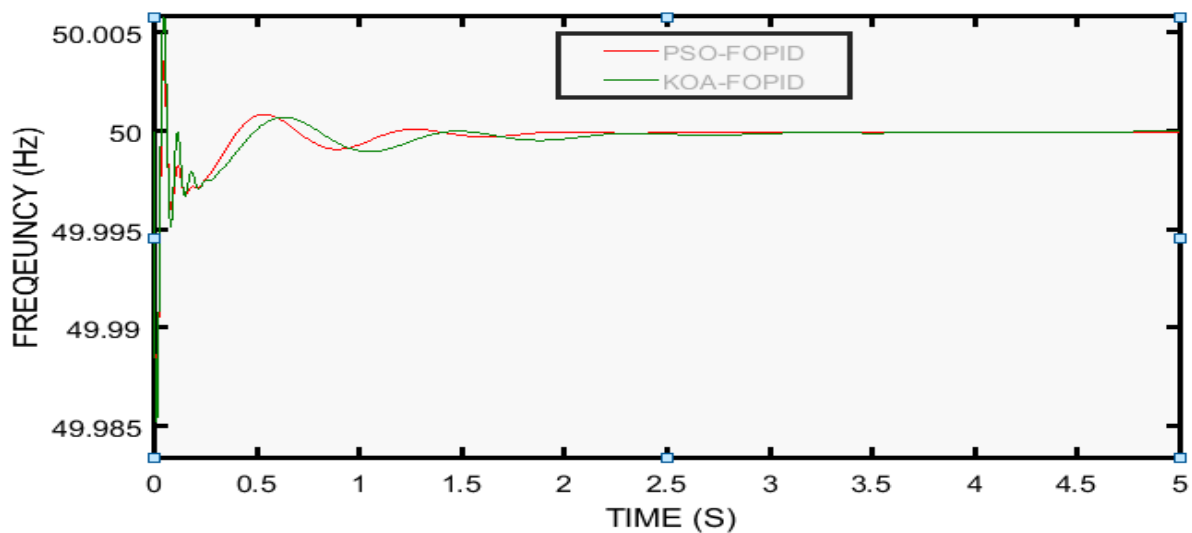
**Figure 6.** Frequency Response (KOA-FOPID)

The frequency response of the PSO-FOPID controller, as shown in Figure 7, highlights its capability to maintain frequency stability under dynamic conditions. The response settles at approximately 4.7 seconds, reaching a steady state very close to the nominal 50 Hz, with only minimal oscillations thereafter.



**Figure 7.** Frequency Response (PSO-FOPID)

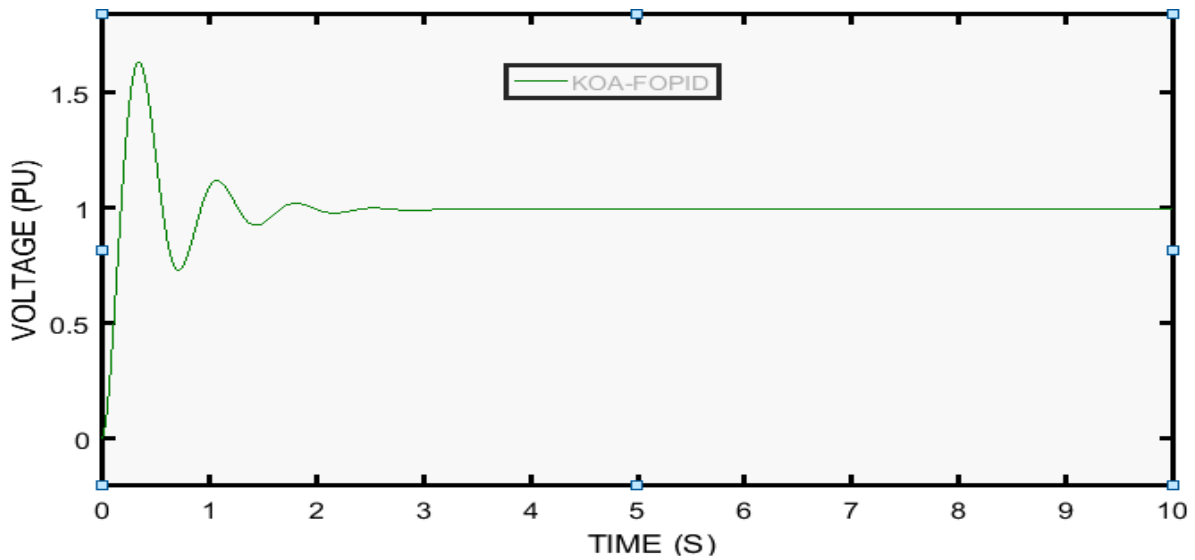
Thus, the combined Frequency Response is represented in Figure 8. It shows how the KOA-FOPID compares to the PSO-FOPID controller.



**Figure 8.** Frequency Response (PSO-FOPID)

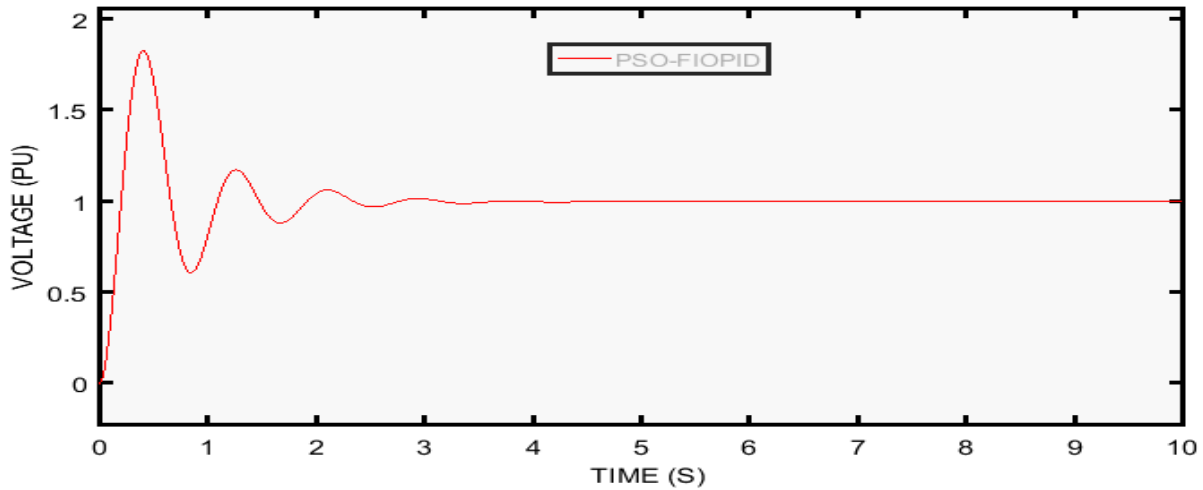
#### 4.2.2 HRES-Based Microgrid Voltage Stability Profile

The results presented in Figure 9, Figure 10 and Figure 11 corresponds to the KOA-FOPID Voltage Controller, PSO-FOPID Voltage Controller, and the Combined Area 1 Voltage Stability Response, respectively. The response in Figure 9 illustrates the power system's voltage behavior following a load disturbance. An initial voltage deviation is observed at the onset, but the controller effectively suppresses the fluctuation, enabling the system to settle at approximately 3.23 seconds.



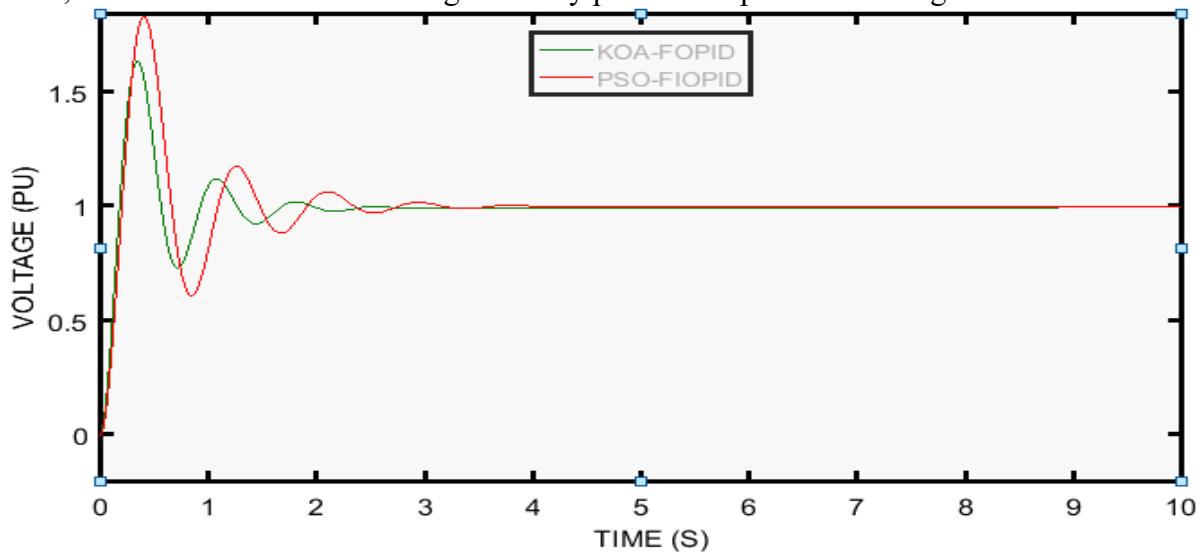
**Figure 9.** Frequency Response (KOA-FOPID)

For the PSO-FOPID controller, Figure 10 shows the voltage profile. The signal experienced initial overshoot and fluctuations. Settling was achieved at approximately 4.37 seconds.



**Figure 10.** Voltage Response (PSO-FOPID)

Thus, the combined AREA 1 voltage stability profile is represented in Figure 11



**Figure 11.** Combined Voltage Response

### 4.3 Performance Index analysis

To quantitatively evaluate the effectiveness of the optimized FOPID controllers, key performance indices were analyzed for both Area 1 and Area 2 of the HRES-based microgrid. The selected indices; overshoot, undershoot, settling time, and rise time provide insight into the dynamic behavior of the system under frequency and voltage disturbances. These metrics serve as critical indicators of controller efficiency in maintaining system stability and ensuring reliable operation.

The results, presented in Table 4.5 for Area 1 and Table 4.6 for Area 2, enable a comparative assessment of the KOA-FOPID and PSO-FOPID controllers in terms of their ability to enhance frequency and voltage stability across different operating conditions.

**Table 4.** Performance Metrics

Performance Index	Frequency Stability Controller		Voltage Stability Controller	
	KOA-FOPID	PSO-FOPID	KOA-FOPID	PSO-FOPID
Overshoot (%)	42.143	25.959	65.833	84.259
Undershoot	24.266	24.947	1.526	1.885
Settling Time (s)	3.62	4.79	3.23	4.37
Rise Time	13.533	15.257	120.06	131.43

The performance indices in Table 4.5 provide a comparative analysis of KOA-FOPID and PSO FOPID controllers for frequency and voltage stability in Area 1 of the HRES-based microgrid. While PSO-FOPID has a good performance in frequency overshoot and voltage settling time, showing its strength in damping and quicker voltage recovery. The KOA-FOPID is superior in frequency rise and settling times and voltage overshoot and undershoot, indicating stronger robustness and stability in managing disturbances.

### 5. CONCLUSION

This study applied a Fractional Order PID (FOPID) controller to enhance frequency and voltage stability in a two-area HRES-based microgrid, with parameters optimized using the Kepler Optimization Algorithm (KOA) and Particle Swarm Optimization (PSO). Comparative results demonstrate that KOA-FOPID provides a faster and more stable dynamic response than PSO-FOPID in regulating both frequency and voltage in the HRES microgrid. For frequency stability, KOA-FOPID achieved shorter settling and rise times (3.62 s, 13.533 s) compared with PSO-FOPID (4.79 s, 15.257 s), with comparable undershoot but higher overshoot. For voltage stability, KOA-FOPID again outperformed PSO-FOPID with reduced settling and rise times (3.23 s, 120.06 s against 4.37 s, 131.43 s), lower overshoot (65.833% against 84.259%), and smaller undershoot. Overall, the KOA-FOPID controller demonstrates superior responsiveness and improved stability performance, making it a more effective option for dynamic control of HRES-based microgrids.

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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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## EXERGY-BASED MODELING AND EVALUATION OF INDUSTRIAL HEATERS USING AN OBJECT-ORIENTED SIMULATION SOFTWARE

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### ABSTRACT

*The Kaduna Refining and Petrochemicals Company (KRPC) Power Plant's Heaters that are used to warm the feed water before it enters the boilers are experiencing deterioration from their design output, which has increased the plant's fuel usage. A mathematical model for the company's Heaters were developed using energy and exergy approach, and a simulation software for assessing the Heaters was developed using C# programming code and validated in open-source literature with a benchmark percentage deviation of 10%. The validated result revealed a maximum deviation of 2.18%, demonstrating the validity of the simulation software. The efficiencies, losses, and destructions of the Heaters were computed under design and operating condition as the input data were compiled and processed. The outcome showed that the energy efficiencies of Heater 1 and 2, which were each 96.99% at design conditions, were reduced to 87.38% and 84.17% at operating conditions, and the exergy efficiencies, which were each 10.20% at design conditions, were reduced to 6.89% and 3.73%. Similar to how exergy destruction increased from 2.5268 MW each at design condition to 3.0619 MW and 3.1659 MW at operating condition, energy losses from 0.2375 MW each at design condition increased to 1.1667 MW and 1.4635 MW at operating condition. Investigation revealed that, the Heaters are more energy and exergy efficient under design conditions than under operating conditions, and under operating conditions, more energy is lost and more exergy is destroyed than under design conditions. Additionally, it has been discovered that under both scenarios, energy efficiency is lower than exergy efficiency.*

### 1.0 INTRODUCTION

Industrial heaters are heating systems that are used in industries, such as factories, warehouses, and manufacturing plants. These heaters are typically larger and more powerful than residential heating systems and are designed to heat large spaces or process materials at high temperatures. There are many different types of industrial heaters, including High Pressure (HP) Heaters. They are used in a variety of applications, including oil and gas processing, petrochemical refining, and power generation to warm the feed water before it enters the boiler (Ibrahim and Rahman, 2014). People must understand energy management in the modern world, so this kind of research is essential (Awad et al., 2018). The analyses are built on the principles of

thermodynamics. Deteriorating HP heater performance has an effect on a plant's overall performance as well (Haider et al., 2014). The ability of the HP heaters to efficiently transfer heat accounts for the bulk of a conventional cogeneration plant's performance. As a result, the effectiveness of these heaters significantly affects the operation of the plant as a whole (Laskowski et al., 2015). The refinery produces fuels including gasoline, kerosene, lubricants, and drums, much to the delight of its clients (KRPC, 2022). The utilities and power plant sectors make up the power plant and utilities (PPU) department. The HP Heater, as depicted in Figure 1, which has been working to heat the feed water before it enters the boiler, is having trouble performing at the level of its design, which results in excessive fuel usage in the power plant.

## **2. SIMULATION**

The simulation software aims to deal with these issues, revealing the magnitude of losses that occur in the HP Heater by detecting the losses, destructions, and efficiencies of the HP Heater. It will also serve as a guide for the company's management regarding the maintenance schedule for the plant (Elghool et al., 2017).

The evaluation not only assesses but also recommends changes to be made to boost the system's efficiency (Yusof et al., 2018). Several .NET Framework-based apps can be produced using Microsoft's C-SHAPE, a cutting-edge, all-purpose, object-oriented programming language. It is an effective language that is frequently used to create Windows programs, mobile applications, online applications, and other types of applications. An interface in C# is a way to define a contract for how a class or struct should interact with other code. The class or struct must then provide an implementation for each of the members of the interface (C# program, 2022).



**Figure 1.** The High-Pressure Heaters

Heat exchangers simulation software was created using Python code and validated using free and open-source literature. High levels of agreement between the validation result and the literature backed up the program's validity (Abubakar et al., 2020). The most exergy degradation was discovered to be coming from the steam generator, and a validated simulation result via MATLAB showed that the theoretical estimate matched the simulation result perfectly (Altarawneh et al., 2022). When a cogeneration facility was analyzed using a MATLAB calculating tool, it was discovered that the steam generator is where the majority of exergy is lost (Kumar et al., 2020).

## **3. RELATED LITERATURES**

According to a study, a degree Celsius difference in water temperature has an impact on the pressure and heating rate of a plant's condenser (Pattanayak et al., 2019). A study reveals that power generation increases in tandem with coal consumption. Energy was destroyed at a rate of roughly 16% more when fuel consumption rose by 40 kg/s (Khaleel et al., 2022). An increase in plant efficiency from 52.3% to 54.15% led to an increase in output from 330 MW to 412 MW, as efficiency and output are strongly correlated (Chen et al., 2022). The appropriate pressures for bleeding off steam are simultaneously obtained for heat exchangers. The highest efficiencies are used to guide a multivariable optimization (Khaleel et al., 2022).

Similarly, the validated results were found to be sufficient when the MATLAB simulation program of a coal-fired power station was evaluated under various load circumstances (Kumar et al., 2019). According to a factory analysis, the combustion chamber loses the most energy (73%), and as the temperature of the surrounding air rises, so do the plant's energy production and efficiency (Bataineh et al., 2020). According to the 1.42% against 10% benchmark verified simulation program analysis, the HP Pumps have greater efficiency under design conditions than under operating conditions, and during operating conditions, more energy is lost and more exergy is destroyed than under design conditions (Abubakar et al., 2022). A study has shown that minimizing the difference between water and steam temperatures leads to a reduction in the amount of energy lost in the plant (Khaleel et al., 2021). Basic tests for verifying asymptotic behavior have been used to validate an object-oriented reciprocating compressor simulation code, ensuring error-free code and physically accurate outcomes (Damle et al., 2011). The step-by-step process for creating the boiler's mathematical model was detailed as the cogeneration plant of a refinery was analyzed (Abubakar et al., 2020). Exergy-based simulation software was developed and verified using open-source literature, and it showed strong correlations in both the qualitative and quantitative dimensions. An energy conversion process plant was then examined using it (Zoder et al., 2018). Software was used to assess a 200 MW power plant. It was discovered that the boiler wasted more energy than the condenser overall (Ahmadi et al., 2016).

### **3. METHODS**

#### **3.1 The Cogeneration Plant**

The deaerators change water from 45°C, 9 bars, and 1 ppm dissolved oxygen to 125°C, 2.5 bars, and 0.007 ppm dissolved oxygen, respectively. After passing through the pumps, the water's pressure increased to 60.5 bars. The water is then heated to 140°C and fed to the steam generators at a rate of 270 t/hr by heaters. At 185°C and 52.4bar, it turns into saturated steam. The steam is heated to a maintained dry temperature of 412°C and 42.5bar at the exit by the superheaters and attemperators.

#### **3.2 Pressure Generation**

High-pressure pumps and electric generators are both run by superheated steam. The medium-pressure steam generated by the pumps and generators powers the lower pumps and heats the water in the heaters; as a result, it condenses through a vacuum and is pushed to the condensate tank, where it is recycled to the Demin unit as depicted in figure 3.1. Deaerators are supplied with steam from the lower pumps and condensate from the heaters (Tokyo, 1981).

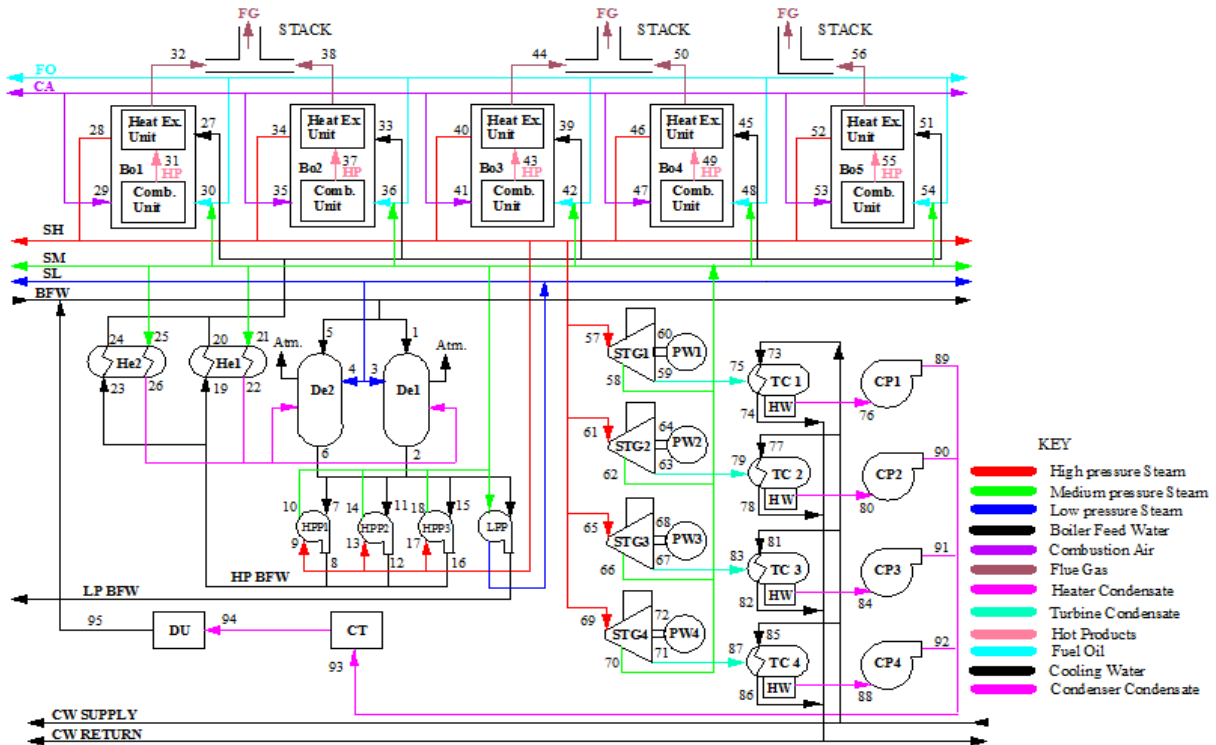


Figure 2. Process of the cogeneration plant

**Nomenclature**

BFW	Boiler feed water
CDT	Condensate
CW	Cooling water
CA	Combustion air
ESM	Extracted medium pressure steam
CSM	Condensed medium pressure steam
De	Deaerator
HPP	High pressure pump
LPP	Low pressure pump
He	Heater
Bo	Boiler
STG	Steam turbine generator
TC	Turbine condenser
HW	Hot well
CP	Condensate pump
CT	Condensate tank
DU	Demineralized unit
CU	Combustion unit
HEU	Heat exchange unit
KRPC	Kaduna refining and petro-chemical company
HHV	high heating value of fuel (kJ/kg)
LHV	low heating value of fuel (kJ/kg)
AAF	actual air-fuel ratio of fuel (kg of air/kg of fuel)
$\dot{E}$	Energy flow rate (kJ/s)
$\dot{E}_X$	Exergy flow rate (kJ/s)
$\dot{E}_{XD}$	Exergy destruction (kJ/s)
$C_p$	Specific heat capacity (kJ/kgK)
M	Mass flow rate (Kg/s)
Q	Rate of heat transfer to the system (kJ/s)

$\dot{Q}_L$	Rate of heat loss (kJ/s)
W	Rate of work done by the system (kJ/s)
PW	Power produce by the system (kJ/s)
h	specific enthalpy (J/Kg)
s	specific entropy (J/Kg K)
$P_o$	Atmospheric pressure (bar)
$T_o$	Atmospheric Temperature (°C)

*Greek letters*

$\eta_I$	Energy efficiency (%)
$\eta_{II}$	Exergy efficiency (%)
$\epsilon$	specific exergy (kJ/Kg)

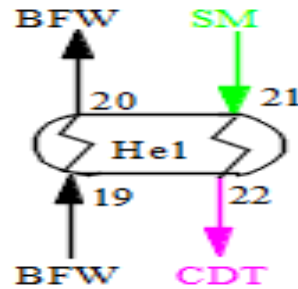
*Sub\_ and superscripts*

SH	High pressure steam
SM	Medium pressure steam
SL	Low pressure steam
FW	Feed water
FO	Fuel oil
F	Fuel
FG	Flue gas
A	Air
S	Steam
comb	Combustion
HP	Hot products
0	reference state

A sketch of the plant's process was made after investigating its operational procedures. The component-wise approach and a review of the thermodynamic laws were used to construct the general thermodynamic model of a component.

### 3.3 Mathematical Model of the High-Pressure Heaters

A generic thermodynamic model and the process of the cogeneration plant were used to build the specific thermodynamic model of the high-pressure heaters. Only heaters 1 and 2, which are seen in Figures 3.2 and 3.3, were examined throughout this research project.



**Figure 3.** High-Pressure Heater 1

### 3.4 Energy Efficiency on High-Pressure Heater 1

Energy efficiency ( $\eta_{I(He1)}$ ):

$$\frac{\text{Energy flowrate of FW outlet} - \text{Energy flowrate of FW inlet}}{\text{Energy flowrate of SM inlet} - \text{Energy flowrate of CDT outlet}} \times 100\%$$

Exergy efficiency ( $\eta_{II(He1)}$ ):

$$\frac{\text{Exergy flowrate of FW outlet} - \text{Exergy flowrate of FW inlet}}{\text{Exergy flowrate of SM inlet} - \text{Exergy flowrate of CDT outlet}} \times 100\%$$

Energy loss ( $\dot{Q}_{L(He1)}$ ):

$$(\text{Energy flowrate of SM inlet} + \text{Energy flowrate of FW inlet}) - (\text{Energy flowrate of FW outlet} + \text{Energy flowrate of CDT outlet})$$

Exergy Destruction ( $\dot{E}_{XD(He1)}$ ):

$$(\text{Exergy flowrate of SM inlet} + \text{Exergy flowrate of FW inlet}) - (\text{Exergy flowrate of FW outlet} + \text{Exergy flowrate of CDT outlet})$$

Where:

$$\text{Energy flowrate of FW inlet } (\dot{E}_{19}) = \dot{M}_{19}h_{19} \quad (1)$$

$$\text{Energy flowrate of FW outlet } (\dot{E}_{20}) = \dot{M}_{20}h_{20} \quad (2)$$

$$\text{Energy flowrate of SM inlet } (\dot{E}_{21}) = \dot{M}_{21}h_{21} \quad (3)$$

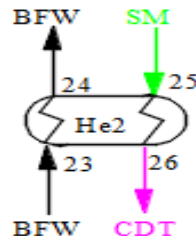
$$\text{Energy flowrate of CDT outlet } (\dot{E}_{22}) = \dot{M}_{22}h_{22} \quad (4)$$

$$\text{Exergy flowrate of BFW inlet } (\dot{E}x_{19}) = h_{19} - T_0s_{19} \quad (5)$$

$$\text{Exergy flowrate of BFW outlet } (\dot{E}x_{20}) = h_{20} - T_0s_{20} \quad (6)$$

$$\text{Exergy flowrate of SM inlet } (\dot{E}x_{21}) = h_{21} - T_0s_{21} \quad (7)$$

$$\text{Exergy flowrate of CDT Outlet } (\dot{E}x_{22}) = h_{22} - T_0s_{22} \quad (8)$$



**Figure 4.** High-Pressure Heater 2

### 3.5 Energy Efficiency on High-Pressure Heater 2

Energy efficiency ( $\eta_{I(He2)}$ ):

$$\frac{\text{Energy flowrate of FW outlet} - \text{Energy flowrate of FW inlet}}{\text{Energy flowrate of SM inlet} - \text{Energy flowrate of CDT outlet}} \times 100\%$$

Exergy efficiency ( $\eta_{II(He2)}$ ):

$$\frac{\text{Exergy flowrate of FW outlet} - \text{Exergy flowrate of FW inlet}}{\text{Exergy flowrate of SM inlet} - \text{Exergy flowrate of CDT outlet}} \times 100\%$$

Energy loss ( $\dot{Q}_{L(He2)}$ ):

$$(\text{Energy flowrate of SM inlet} + \text{Energy flowrate of FW inlet}) - (\text{Energy flowrate of FW outlet} + \text{Energy flowrate of CDT outlet})$$

Exergy Destruction ( $\dot{E}_{XD(He2)}$ ):

$$(\text{Exergy flowrate of SM inlet} + \text{Exergy flowrate of FW inlet}) - (\text{Exergy flowrate of FW outlet} + \text{Exergy flowrate of CDT outlet})$$

Where:

$$\text{Energy flowrate of FW inlet } (\dot{E}_{23}) = \dot{M}_{23}h_{23} \quad (9)$$

$$\text{Energy flowrate of FW outlet } (\dot{E}_{24}) = \dot{M}_{24}h_{24} \quad (10)$$

$$\text{Energy flowrate of SM inlet } (\dot{E}_{25}) = \dot{M}_{25}h_{25} \quad (11)$$

$$\text{Energy flowrate of CDT outlet } (\dot{E}_{26}) = \dot{M}_{26}h_{26} \quad (12)$$

$$\text{Exergy flowrate of BFW inlet } (\dot{E}x_{23}) = h_{23} - T_0s_{23} \quad (13)$$

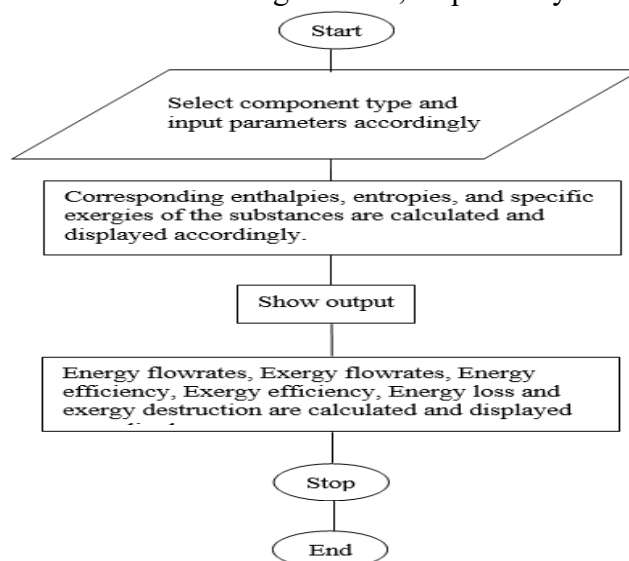
$$\text{Exergy flowrate of BFW outlet } (\dot{E}x_{24}) = h_{24} - T_0s_{24} \quad (14)$$

$$\text{Exergy flowrate of SM inlet } (\dot{E}x_{25}) = h_{25} - T_0s_{25} \quad (15)$$

$$\text{Exergy flowrate of CDT outlet } (\dot{E}x_{26}) = h_{26} - T_0s_{26} \quad (16)$$

### 3.6 Simulation Software of the High-Pressure Heaters

The simulation software, which comprises the programming codes and users' interfaces, was designed and implemented using the C# programming language. These interfaces include the menu preparation, component selection, input data, and output data interfaces. The flowchart of algorithms and interfaces is shown in Figures 5–9, respectively.



**Figure 5.** Simulation algorithm

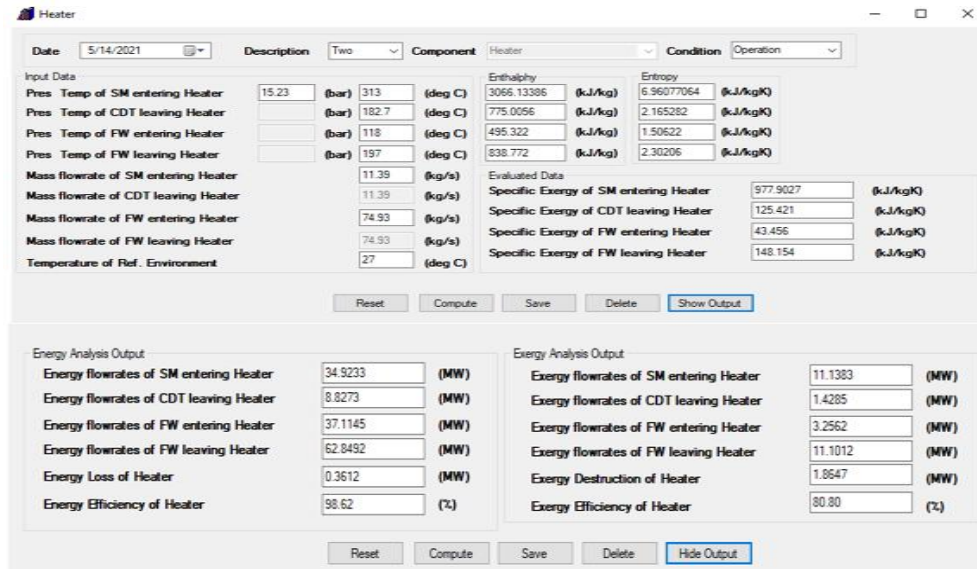


Figure 6. Literature input data, with simulation output data

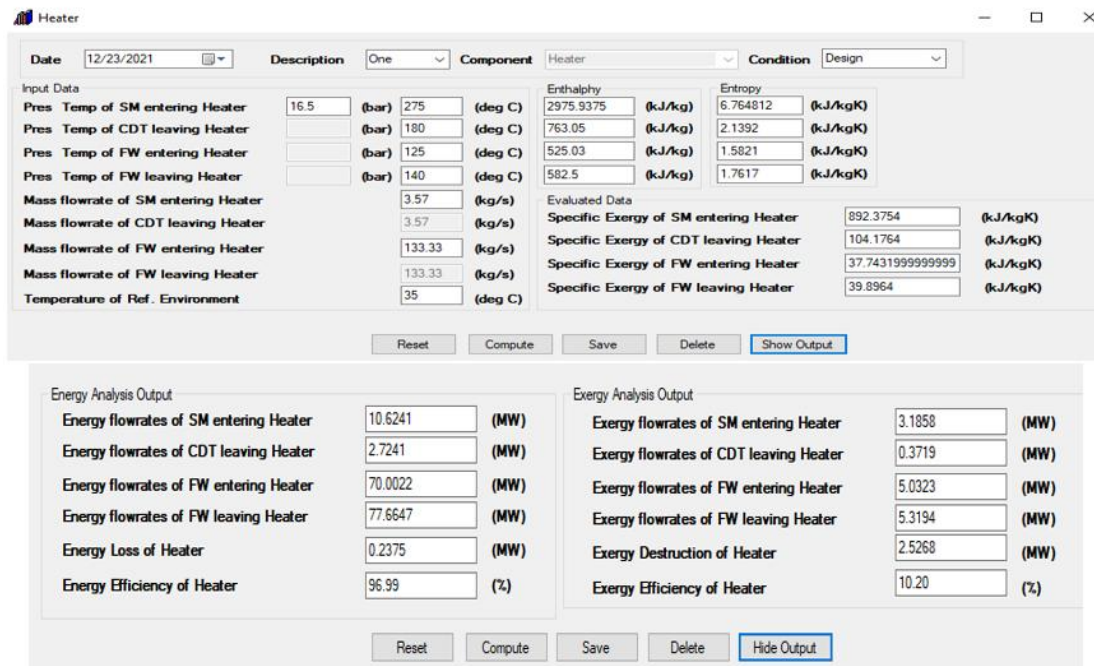


Figure 7. HP Heater interphase at design condition

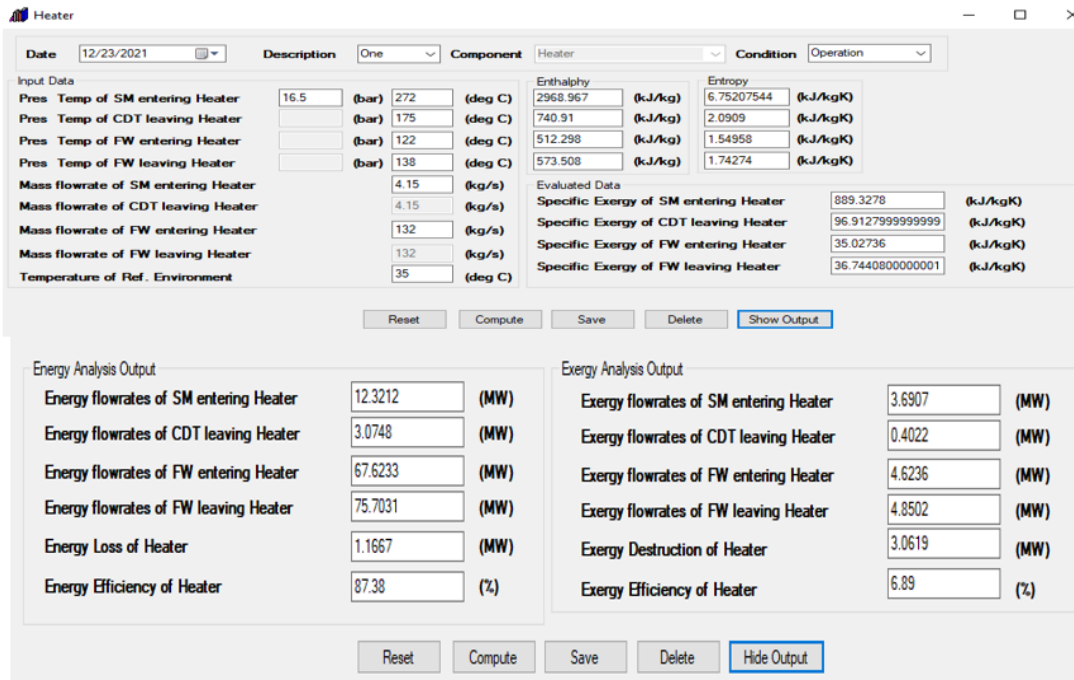


Figure 8. HP Heater 1 interphase at operating condition

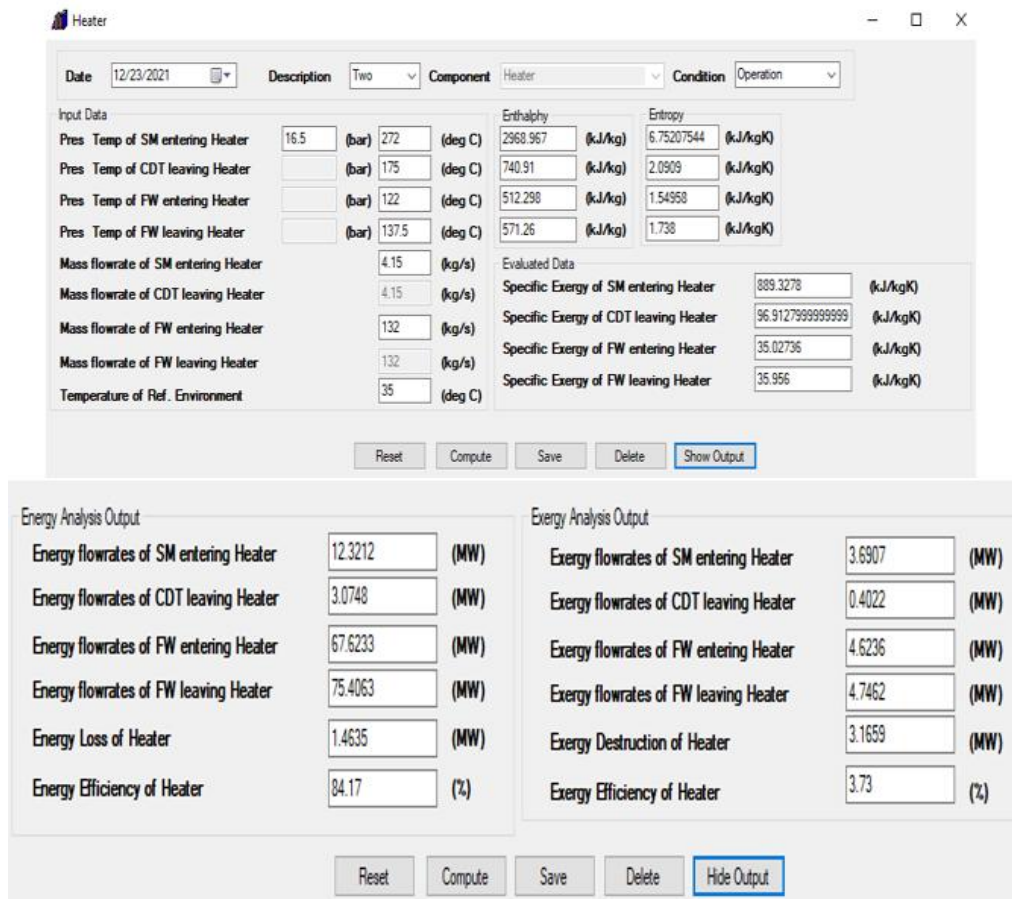


Figure 9.: HP Heater 2 interphase at operating condition

### 3.7 Validation of the Simulation Software

Table 3.1 shows the input data together with the high-pressure heater's associated enthalpy and entropy for both cases. The outputs of the software and those of an Indian power plant using free and open-source literature were compared, with a benchmark percentage error of 10% (Pilankar and Kale 2016). The validated result revealed a maximum inaccuracy of 2.18%, which might have been brought on by some default assumptions and settings. As a result, this confirms the accuracy of the simulation software as displayed in tables 3.2 and 3.3.

**Table 1.** Input data of hp heater at literature and simulation condition

Component	Point	Fluid Type	Input			Literature		Simulation	
			Pressure (bar)	Temperature (°C)	Mass flowrate (kg/s)	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)
HP Heater	15a	SM in	15.23	313	11.39	3066.48	6.962	3066.1339	6.9608
	3a	CDT out	10.66	183	11.39	776.68	2.169	775.0056	2.1653
	9a	FW in	127.52	118	74.93	495.80	1.474	495.322	1.5062
	10a	FW out	127.52	197	74.93	843.84	2.285	838.772	2.3021

**Table 2.** Enthalpy and entropy percentage error

Component	Point	Fluid Type	Enthalpy (kJ/kg)	Enthalpy (kJ/kg)	% Error	Entropy (kJ/kg.K)	Entropy (kJ/kg.K)	% Error
			Literature	Simulation		Literature	Simulation	
HP Heater	15a	SM in	3066.48	3066.1339	0.01	6.962	6.9608	0.02
	3a	CDT out	776.68	775.0056	0.22	2.169	2.1653	0.17
	9a	FW in	495.80	495.322	0.10	1.474	1.5062	2.18
	10a	FW out	843.84	838.772	0.60	2.285	2.3021	0.75

**Table 3.** Analysis Index Percentage Error

Component	Analysis Index	Literature	Simulation	% Error
HP Heater	Energy Efficiency (%)	100	98.62	1.38
	Energy Loss (MW)	0.366	0.3612	1.31
	Exergy Efficiency (%)	80.19	80.8	0.76
	Exergy Destruction (MW)	1.889	1.8647	1.29

### 3.8 Evaluation of the HP Heaters

The flow rates of the heaters at each location were estimated and indicated as the input data were collected and processed. The heaters' efficiencies, energy losses, and exergy destructions are then independently estimated under design and operational conditions. Tables 3 and 4 display the input data and the contrasted analytical outputs for the heaters under design and operational conditions.

**Table 4.** Input Data of HP Heaters at Design and Operating Condition

Component	Point	Fluid Type	Pressure (bar)	Temperature (°C)	Mass flowrate (kg/s)	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)	Specific exergy (kJ/kg.K)	Energy flowrate (MW)	Exergy flowrate (MW)
DESIGN CONDITION										
HP Heater	19	FW in	-	125	133.33	525.03	1.5821	37.74319999	70.0022	5.0323
	20	FW out	-	140	133.33	582.5	1.7617	39.8964	77.6647	5.3194
	21	SM in	16.5	275	3.57	2975.938	6.764812	892.3754	10.6241	3.1858
	22	CDT out	-	180	3.57	763.05	2.1392	104.1764	2.7241	0.3719
OPERATING CONDITION										
HP Heater 1	19	FW in	-	122	132	512.298	1.54958	35.02736	67.6233	4.6236
	20	FW out	-	138	132	573.508	1.74274	36.74408	75.7031	4.8502
	21	SM in	16.5	272	4.15	2968.967	6.75207544	889.3278	12.3212	3.6907
	22	CDT out	-	175	4.15	740.91	2.0909	96.9127999	3.0748	0.4022
HP Heater 2	23	FW in	-	122	132	512.298	1.54958	35.02736	67.6233	4.6236
	24	FW out	-	137.5	132	571.26	1.738	35.956	75.4063	4.7462
	25	SM in	16.5	272	4.15	2968.967	6.75207544	889.3278	12.3212	3.6907
	26	CDT out	-	175	4.15	740.91	2.0909	96.9127999	3.0748	0.4022

**TABLE 5.** Comparison Between Design and Operating Condition

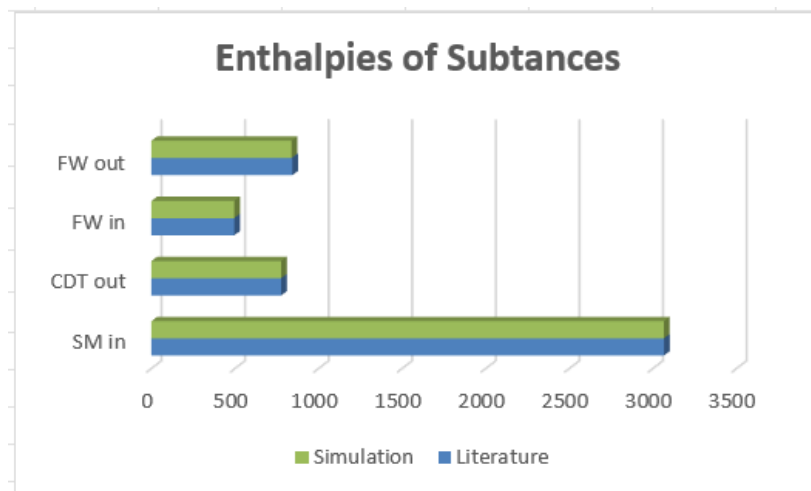
Component	Analysis index	Condition		Difference
		Design	Operating	
HP Heater 1	Energy Efficiency (%)	96.99	87.38	9.61
	Energy Loss (MW)	0.2375	1.1667	0.93
	Exergy Efficiency (%)	10.20	6.89	3.31
	Exergy Destruction (MW)	2.5268	3.0619	0.54
HP Heater 2	Energy Efficiency (%)	96.99	84.17	12.82
	Energy Loss (MW)	0.2375	1.4635	1.23
	Exergy Efficiency (%)	10.20	3.73	6.47
	Exergy Destruction (MW)	2.5268	3.1659	0.64

#### 4. RESULTS AND DISCUSSION

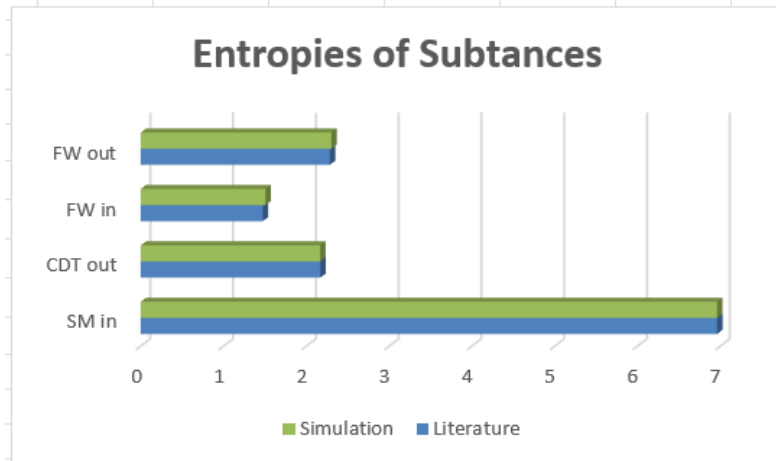
In the case of validation, the outputs from the software for the high-pressure heater were contrasted with the norm in the literature. But when assessing the heaters, similar comparisons were made between the operating circumstances and design outcomes. The percentage errors and variances that were discovered are displayed on the accompanying graphs.

##### 4.1 Validation Analysis of the Software

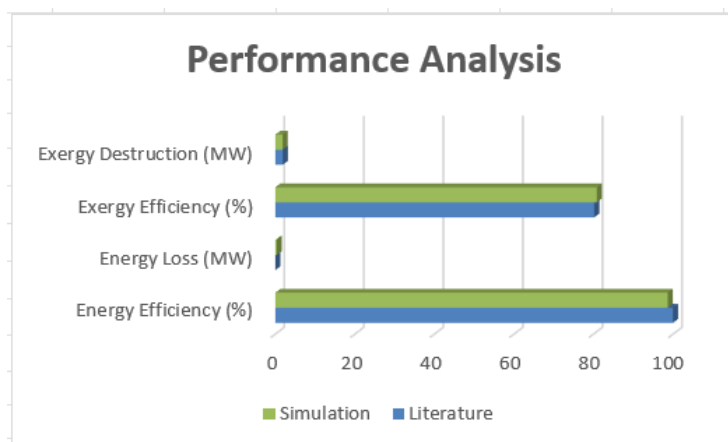
The percentage inaccuracy of the analysis ranges from 0.01% to 2.18%. In the entropy of water entering the heater, the greatest percentage error of 2.18%, which is less than the benchmark of 10%, was discovered. Figures 10, 11, and 12 present these inaccuracies in pictorial form, accordingly.



**Figure 10.** Enthalpy variance at both scenarios



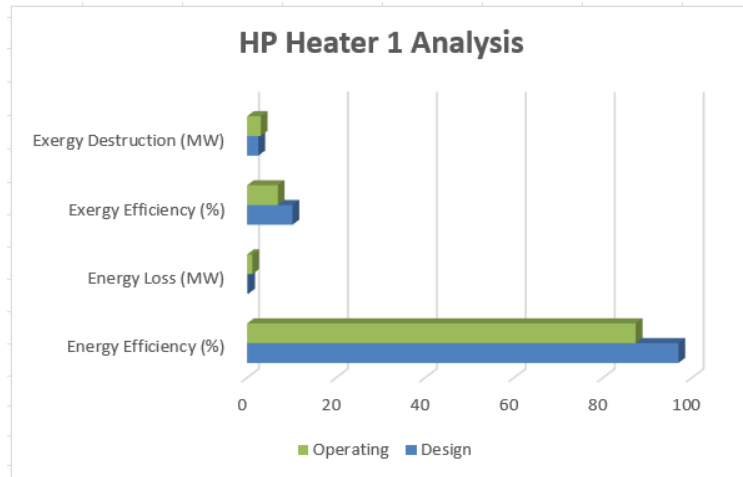
**Figure 11.** Entropy variance at both scenarios



**Figure 12.** Analysis indices variance at both scenarios

#### 4.2 Performance Analysis of HP Heater 1

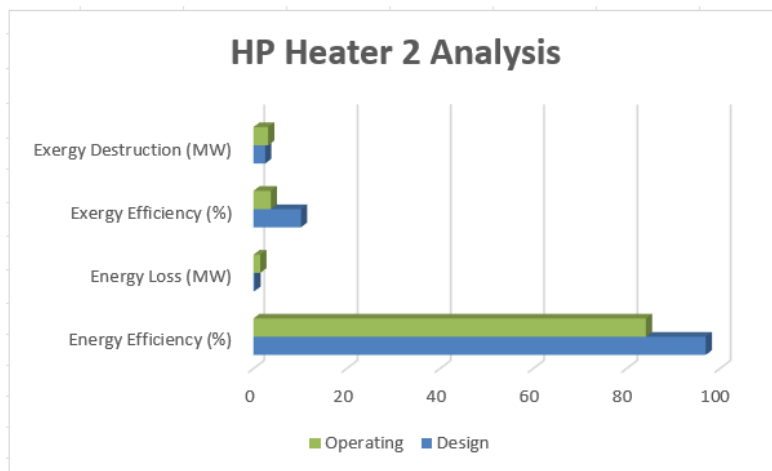
Performance analysis has been done on HP Heater 1 of the power plant under design and operational circumstances. Figure 4.4 shows the performance index graph. The graph shows that energy and exergy efficiency, which were 96.99% and 10.20% at design condition, are now 87.38% and 6.89%, respectively, while energy loss and exergy destruction, which were 0.2375 MW and 2.5268 MW at design condition, are now 1.1667 MW and 3.0619 MW, respectively, at operating condition.



**Figure 13.** Performance index of HP Heater 1 at both conditions

### 4.3 Performance Analysis of HP Heater 2

A performance evaluation of HP Heater 2 in the power plant was carried out under both design and operational conditions. Figures 13 and 14 depict the performance index graph. The graph shows that the energy and exergy efficiency, which were 96.99% and 10.20% at design condition, were reduced to 84.17% and 3.73% at operating condition, while the energy loss and exergy destruction, which were 0.2375 MW and 2.5268 MW at design condition, were increased to 1.4635 MW and 3.1659 MW, respectively.



**Figure 14.** Performance indices of HP Heater 2 at both conditions

## 5. CONCLUSION

This study encourages the creation of simulation software using object-oriented programming languages. The HP Heater thermodynamic model, which was converted into a simulation software, had a maximum percentage error of 2.18% when compared to the benchmark percentage error of 10%. This demonstrated the model's applicability. The investigation showed that the HP Heaters at the KRPC power plant had higher energy and exergy efficiency at design than in operating conditions, and there is greater energy loss and exergy destruction in operating conditions than in design conditions. These are a result of the power plant's defective control system.

As a result, the KRPC power plant's control system needs to be in good working order if it is not constantly operated at design conditions. The company's management will receive sound direction regarding how to maintain the plant. Furthermore, it is anticipated that this research endeavor will be of utmost importance to scientists, educators, and professionals in energy science and engineering.

### **Acknowledgement**

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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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## AI-POWERED SMART GRIDS: OPTIMIZING ENERGY SYSTEMS IN DEVELOPING COUNTRIES – NIGERIA AS A CASE STUDY

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### ABSTRACT

*The global transition toward sustainable and resilient energy systems necessitates the modernization of legacy power infrastructure into intelligent, self-healing Smart Grids. While developed nations focus on integrating distributed renewable energy, developing countries face the more fundamental challenge of addressing chronic grid instability, high technical and non-technical losses (NTL), and a significant energy access deficit. This paper investigates the transformative potential of Artificial Intelligence (AI) and Digital Twin (DT) technologies in addressing these unique challenges, using Nigeria as a critical case study. Nigeria, with its recurrent national grid collapses and estimated 40-50% total system losses, represents a microcosm of the energy crisis in the developing world. We review the application of AI/Machine Learning models, such as Convolutional Neural Networks (CNN) and Long Short-Term Memory (LSTM) networks, for enhancing load forecasting accuracy in volatile demand environments (Eya, 2023; Gafai, 2022). Furthermore, we detail the use of AI-driven anomaly detection for combating pervasive NTL (electricity theft and meter bypass), a major financial drain on the sector (Hashim et al., 2024). The paper then explores the role of Digital Twin technology in creating virtual, real-time replicas of aging transmission and distribution assets, enabling predictive maintenance, optimizing asset life-cycle management, and simulating the impact of new infrastructure on the unstable grid. Finally, we analyze the critical implementation barriers, including data scarcity, human capital deficits, and institutional inertia, and propose a phased, data-centric policy roadmap for the successful adoption of AI-powered Smart Grids in Nigeria and similar developing economies. The convergence of these advanced digital technologies offers a viable pathway to achieving grid stability, reducing losses, and ultimately closing the energy access gap.*

### 1.0 INTRODUCTION

#### 1.1 Global Energy Transition and the Smart Grid Imperative

The 21st century has brought an unprecedented confluence of challenges to the global energy sector: the imperative to decarbonize energy sources to mitigate climate change, the need to

accommodate decentralized and intermittent renewable energy sources (RES), and the growing demand for reliable, high-quality power. The traditional, centralized power grid architecture is ill-equipped to handle these complexities. Consequently, the concept of the **Smart Grid**—an electricity network that uses digital communication technology to detect and react to local changes in demand and supply has become the global standard for modernizing power infrastructure. Smart Grids promise enhanced efficiency, improved reliability, and the seamless integration of distributed energy resources (DERs) (Eleks, 2024).

### **1.2 The Unique Context of Developing Countries**

While Smart Grid deployment in developed nations primarily focuses on optimizing the integration of high-penetration renewables, the context in developing countries is fundamentally different and often more challenging. Nations in sub-Saharan Africa, South Asia, and parts of Latin America grapple with a legacy of aging, poorly maintained infrastructure, chronic power deficits, and pervasive system losses (Belge et al., 2024). The core objective is not merely optimization but achieving basic grid stability and extending energy access to underserved populations.

Nigeria, as Africa's largest economy and most populous nation, serves as a compelling and critical case study. Despite vast natural gas reserves and significant installed generation capacity, the country suffers from a severely constrained and unreliable power system characterized by frequent grid collapses, high operational costs, and a massive energy access gap, with millions relying on expensive and polluting self-generation (Onakowoicho, 2025). The successful application of advanced digital technologies in Nigeria could provide a scalable blueprint for energy sector transformation across the developing world.

### **1.3 AI and Digital Twin as Transformative Technologies**

The recent advancements in Artificial Intelligence (AI) and Digital Twin (DT) technologies offer powerful tools uniquely suited to address the systemic failures of developing-world grids. AI, particularly Machine Learning (ML) and Deep Learning (DL), excels at pattern recognition, prediction, and anomaly detection—functions directly applicable to optimizing grid operations, forecasting volatile load, and identifying system inefficiencies. The Digital Twin, a virtual, real-time replica of a physical asset or system, provides a risk-free environment for simulating complex grid interactions, testing optimization strategies, and enabling highly accurate predictive maintenance (ConsultQE, 2025). This paper argues that the synergistic application of AI and DT is not merely an enhancement but a necessary foundation for the successful implementation of a resilient Smart Grid in Nigeria.

The scope of this review is to systematically analyze the application of AI and DT in three critical areas for the Nigerian power sector: optimization of energy systems (load forecasting), reduction of system losses (NTL detection), and management of aging assets (predictive maintenance and simulation).

## **2.0 The Nigerian Energy Landscape: Challenges and Opportunities**

The Nigerian power sector is characterized by a complex interplay of technical, financial, and institutional challenges that have historically constrained its growth and reliability. Understanding this context is crucial for designing effective digital interventions.

### **2.1 Grid Instability and Collapse**

The most visible symptom of the sector's fragility is the recurrent national grid collapse. The grid, managed by the Transmission Company of Nigeria (TCN), is often described as a

"nervous system" prone to frequent failures, sometimes collapsing multiple times a year (Olaniwun Ajayi, 2025). The root causes are multi-faceted:

- *Aging Infrastructure*: Much of the transmission and distribution network was built decades ago and has not been adequately maintained or upgraded to handle current load demands. The average age of key transmission assets often exceeds their design life, leading to frequent component failures.
- *Inadequate Transmission Capacity*: The transmission network acts as a bottleneck, unable to evacuate the full capacity generated by power plants, leading to generation curtailment and system instability. The radial nature of the grid, with few redundant paths, means that a single fault can cascade into a national blackout.
- *Lack of Real-Time Monitoring*: The absence of comprehensive, real-time Supervisory Control and Data Acquisition (SCADA) systems across the entire network hinders operators' ability to quickly diagnose and isolate faults, prolonging system blackouts. The TCN reports average transmission losses of 7.79 megawatts for every 100 megawatts transmitted, a figure indicative of systemic inefficiency (Reuters, 2024).

## **2.2 Technical and Non-Technical Losses (NTL)**

Nigeria suffers from some of the highest system losses globally, estimated to be between 40% and 50% of generated power (Online Scientific Research, 2024). These losses are categorized as:

- *Technical Losses*: Power dissipated as heat during transmission and distribution, primarily due to aging equipment, undersized conductors, and long distribution lines. These losses are compounded by poor power factor and unbalanced loads.
- *Non-Technical Losses (NTL)*: Losses due to commercial irregularities, including electricity theft, meter bypass, billing fraud, and uncollected revenue. NTL is a massive financial drain, undermining the financial viability of the Distribution Companies (DisCos) and discouraging private investment (Abro et al., 2025). Recent reports indicate that over 68% of consumers may be bypassing prepaid meters, highlighting the scale of the NTL crisis (The Electricity Hub, 2025). The financial impact of NTL is estimated to be in the billions of Naira annually, creating a vicious cycle of underinvestment and poor service delivery.

## **2.3 Energy Access and the Role of Decentralization**

Despite being a major oil and gas producer, Nigeria has one of the world's largest energy access deficits. While the national grid reaches approximately 60% of the population, the power is often unreliable, leaving an estimated 86 million people without access to reliable electricity (IEEE Spectrum, 2025). This deficit has spurred the rapid growth of decentralized solutions:

- *Mini-Grids and Off-Grid Solutions*: Solar mini-grids and solar home systems are increasingly filling the gap, providing reliable power to rural and underserved communities. This decentralized model, while essential for energy access, adds complexity to future grid planning and integration. The Nigerian government's focus on mini-grids, such as the \$3.2 million solar mini-grid pilot, is sparking a clean energy revolution across emerging markets (Forbes, 2025).
- *Self-Generation*: Businesses and households rely heavily on diesel and petrol generators, leading to high operational costs, noise pollution, and significant carbon emissions. This reliance on self-generation further reduces the load on the national grid, making accurate forecasting more difficult and contributing to the financial woes of the DisCos.

## **2.4 Data Infrastructure Readiness**

The foundation of any AI or DT implementation is data. Nigeria's power sector currently faces a significant data challenge:

- **Poor Metering:** The lack of universal smart metering means that consumption data is often estimated or based on manual readings, leading to inaccuracies and facilitating NTL. The current metering infrastructure is insufficient to provide the granular, real-time data required for advanced AI/DT applications.
- **Fragmented Data Systems:** Data collection is often fragmented across different DisCos and TCN, with limited standardization and real-time data exchange capabilities. This lack of a unified data platform is a major impediment to system-wide optimization and the creation of a comprehensive Digital Twin of the national grid.

**Table 1.** Nigeria’s power sector challenges

Challenge Area	Specific Problem in Nigeria	Impact on Grid	Digital Focus	Solution
Grid Stability	Recurrent national grid collapses, aging T&D infrastructure	Frequent blackouts, economic disruption, generation curtailment	Digital (Simulation, PdM)	Twin
System Losses	40-50% total losses, high NTL (theft, bypass)	Financial insolvency of DisCos, lack of investment	AI/ML Detection, Forecasting)	(NTL Load
Energy Access	86 million people without reliable power, reliance on self-generation	Economic stagnation, environmental pollution	DT Integration), (Microgrid Optimization)	(DER AI
Data Readiness	Poor metering, fragmented SCADA systems	Inaccurate forecasting, inability to detect real-time faults	Policy Metering), AI Imputation)	(Smart Data

### 3. AI APPLICATIONS FOR GRID OPTIMIZATION IN THE NIGERIAN CONTEXT

Artificial Intelligence (AI) and its sub-fields, Machine Learning (ML) and Deep Learning (DL), provide the computational intelligence necessary to transform raw grid data into actionable insights. In the Nigerian context, AI applications are strategically focused on mitigating the most pressing operational and financial challenges: volatile load, high non-technical losses, and poor asset reliability.

#### 3.1 Load Forecasting and Demand-Side Management (DSM)

Accurate load forecasting is the cornerstone of efficient grid operation, directly impacting generation scheduling, reserve capacity planning, and operational costs. In Nigeria, load demand is highly volatile due to frequent grid outages, the reliance on self-generation, and unpredictable weather patterns. Traditional statistical models often fail to capture these complex, non-linear dynamics.

- **Advanced AI/ML Models:** Recent research has demonstrated the superiority of advanced ML models for load prediction in the Nigerian power system. Studies have successfully applied Artificial Neural Networks (ANN) for short-term load forecasting (STLF) in regions like Abuja, showing improved accuracy over conventional methods (Gafai, 2022). More sophisticated models, such as Convolutional Neural Networks (CNN) combined with Long Short-Term Memory (LSTM) networks (CNN-LSTM), are being explored to capture both the spatial and temporal dependencies in load data, which is crucial for predicting demand in a fragmented grid (Eya, 2023). The integration of external factors, such as socio-

economic indicators and public holidays, further enhances the predictive accuracy of these models.

- *AI-Driven DSM:* Beyond forecasting, AI enables sophisticated Demand-Side Management (DSM). By analyzing historical consumption patterns, weather data, and real-time pricing signals, AI algorithms can predict peak demand events and automatically or semi-automatically adjust the load of participating consumers. This capability is vital for the Nigerian grid, allowing operators to manage peak demand without resorting to load shedding, thereby improving stability and reducing the need for expensive, high-cost generation. AI can also optimize the charging and discharging cycles of battery storage systems, maximizing their contribution to grid stability.

### **3.2 Non-Technical Loss (NTL) Detection**

Non-Technical Losses (NTL), primarily due to electricity theft and meter tampering, represent a major threat to the financial sustainability of the Nigerian power sector. AI/ML offers the most effective defense against this challenge by identifying anomalous consumption patterns that are invisible to manual inspection.

- *Anomaly Detection Models:* The core of AI-driven NTL detection is anomaly detection. This involves training models on historical, legitimate consumption data to establish a "normal" profile. Any significant deviation from this profile is flagged as a potential NTL event.
  - *Supervised Learning:* Models like Support Vector Machines (SVM) and Random Forests are used when a dataset of known fraudulent and non-fraudulent consumers is available.
  - *Unsupervised Learning:* Clustering algorithms, such as K-Means or DBSCAN, are employed to group consumers with similar consumption behaviors. Outliers that do not fit into any established cluster are then investigated as potential thieves.
- *Deep Learning for Feature Extraction:* More advanced approaches utilize Deep Learning, such as Stacked Autoencoders or Recurrent Neural Networks (RNNs), to automatically extract complex features from raw consumption time-series data, leading to higher detection accuracy and a lower false-positive rate (Hashim et al., 2024). The successful deployment of these systems is projected to significantly reduce the 40-50% system losses, injecting much-needed revenue into the DisCos for infrastructure investment. The use of federated learning is also being explored to allow DisCos to share NTL detection models without sharing sensitive customer data.

### **3.3 Fault Detection and Predictive Maintenance (PdM)**

The aging infrastructure in Nigeria is highly susceptible to sudden failures, leading to localized outages and contributing to grid instability. AI-driven Predictive Maintenance (PdM) offers a proactive solution by shifting from reactive (fix-after-failure) or time-based (scheduled) maintenance to condition-based maintenance.

- *Sensor Data Analysis:* By analyzing data streams from sensors (e.g., temperature, vibration, oil quality) on critical assets like transformers and circuit breakers, ML algorithms can learn the "health signature" of the equipment.
- *Failure Prediction:* Models like Hidden Markov Models (HMM) or LSTM networks can predict the remaining useful life (RUL) of an asset, allowing maintenance to be scheduled precisely when needed, before a catastrophic failure occurs. This not only improves grid reliability but also optimizes maintenance budgets, a critical consideration for financially constrained utilities in Nigeria. PdM can also be applied to the transmission network by analyzing data from phasor measurement units (PMUs) to detect subtle anomalies indicative of impending line faults.

### **3.4 AI for Renewable Energy Integration and Microgrid Optimization**

As Nigeria increases its adoption of solar and hydro power, AI becomes essential for managing the intermittency of these sources.

- *Forecasting Renewable Generation:* AI models can accurately forecast solar irradiance and wind speed, allowing grid operators to predict the output of renewable energy plants hours or days in advance. This is crucial for maintaining the generation-demand balance and preventing frequency fluctuations that can lead to grid collapse.
- *Microgrid Control:* For the growing number of mini-grids, AI can optimize the dispatch of power between solar PV, battery storage, and diesel generators. Reinforcement Learning (RL) algorithms are particularly effective here, learning optimal control policies in real-time to minimize fuel consumption and maximize the use of clean energy, thereby reducing the cost of electricity for rural communities.

## **4. DIGITAL TWIN TECHNOLOGY FOR ASSET AND SYSTEM MANAGEMENT**

While AI provides the intelligence for optimization, **Digital Twin (DT)** technology provides the virtual platform for simulation, testing, and real-time monitoring. A DT is a dynamic, virtual replica of a physical asset, process, or system, continuously updated with real-time data from its physical counterpart. For the Nigerian power sector, DTs are invaluable for managing aging assets and simulating the complex dynamics of an unstable grid.

### **4.1 Digital Twin Fundamentals in Power Systems**

The DT concept is built on three pillars: the **Physical Asset** (e.g., a substation), the **Virtual Model** (a high-fidelity simulation), and the **Data Link** (real-time data flow between the two). In the context of the Nigerian grid, DTs offer a safe, virtual environment to:

- *Test Interventions:* Simulate the impact of a new transmission line or a major substation upgrade before physical construction begins.
- *Train Operators:* Provide realistic training scenarios for grid operators, including simulating grid collapse and recovery procedures.
- *Real-Time Monitoring:* Provide a unified, 3D visualization of asset health and operational status, overcoming the limitations of fragmented SCADA systems. The DT acts as a single source of truth for all asset information.

### **4.2 Application in Transmission and Distribution (T&D) Asset Management**

The application of DTs to the T&D network is crucial for extending the life and improving the reliability of Nigeria's aging infrastructure.

- *Substation and Transformer DTs:* Creating DTs of critical substations allows for continuous, real-time monitoring of key performance indicators (KPIs) like temperature, load, and partial discharge. The DT can predict component failure with high accuracy, enabling PdM strategies that prevent catastrophic outages. This is particularly relevant for Nigeria, where transformer failure is a common cause of localized blackouts. The DT can also optimize the tap-changer settings of transformers to maintain optimal voltage levels and reduce technical losses.
- *Transmission Line Optimization:* DTs of transmission lines can be used to calculate Dynamic Line Rating (DLR). By incorporating real-time weather data (temperature, wind speed) into the DT, operators can determine the maximum safe current a line can carry at any given moment, often exceeding the static, conservative rating. This effectively increases the capacity of the existing transmission network without costly physical upgrades, a significant advantage for the TCN (ConsultQE, 2025). Furthermore, DTs can

model the physical sag and tension of lines, preventing failures due to extreme weather conditions.

### **4.3 Digital Twin for Grid Planning and Simulation**

The DT moves beyond individual asset management to system-level optimization, which is paramount for a grid prone to collapse.

- *Grid Collapse Simulation:* A DT of the entire national grid can be used to simulate various fault and collapse scenarios. By running these simulations, operators can identify weak points in the network, optimize protection settings, and develop automated, rapid recovery protocols to minimize blackout duration. This capability is essential for improving the resilience of the Nigerian grid.
- *Integration of DERs:* As mini-grids and solar farms proliferate, the DT becomes essential for modeling their impact on the main grid. It allows planners to simulate the effect of intermittent renewable generation on grid stability and design optimal interconnection points and control strategies for future grid-tied operations. The DT can model the bi-directional power flow introduced by DERs, a phenomenon the current radial grid was not designed to handle.

### **4.4 Synergy of AI and Digital Twin: The Closed-Loop Smart Grid**

The true power lies in the synergy between AI and DT. This integration creates a **closed-loop control system** that is the hallmark of a truly intelligent grid.

- *AI-Enhanced DT:* AI models, such as those used for load forecasting (Section IV.1) and NTL detection (Section IV.2), provide the input data (predicted load, predicted NTL, predicted asset health) that drives the DT simulation. The DT uses these AI-derived predictions to run "what-if" scenarios, such as "What is the optimal generation schedule given the predicted load and the predicted NTL for the next 24 hours?"
- *DT-Trained AI:* Conversely, the DT generates vast amounts of synthetic, high-fidelity data that can be used to train and refine the AI models, especially in data-scarce environments like Nigeria. For instance, the DT can simulate thousands of grid collapse scenarios, generating labeled data that can be used to train an AI model to automatically detect and isolate faults in the real-world grid. This continuous feedback loop—AI informs the DT, and the DT trains the AI—is the mechanism for a self-improving, self-healing grid. This synergy is particularly critical in the Nigerian context where historical data is often unreliable or incomplete (Onile, 2024).

## **5. IMPLEMENTATION CHALLENGES AND POLICY RECOMMENDATIONS**

While the technological potential of AI and Digital Twins is clear, their successful implementation in the Nigerian power sector is contingent upon overcoming significant non-technical barriers related to data, infrastructure, human capital, and governance.

### **5.1 Data and Infrastructure Challenges**

The most immediate hurdle is the **data scarcity and quality deficit**. AI and DT models are data-hungry, yet the Nigerian grid operates with fragmented, often manual, and non-standardized data collection systems.

- *Lack of Smart Metering:* The absence of universal smart metering means that real-time, granular consumption data—the lifeblood of NTL detection and accurate forecasting—is largely unavailable. The current metering infrastructure is insufficient to provide the granular, real-time data required for advanced AI/DT applications.
- *Legacy SCADA Systems:* Existing Supervisory Control and Data Acquisition (SCADA) systems are often outdated, siloed, and lack the necessary communication bandwidth and

security protocols to support real-time DT data feeds. Upgrading these systems is a massive capital investment challenge.

- *Communication Infrastructure:* The reliability and bandwidth of the national communication network (e.g., fiber optics, 4G/5G) in remote areas are insufficient to support the continuous, high-volume data exchange required for a fully operational DT of the entire grid. Investment in a dedicated, secure communication network is non-negotiable.

### **5.2 Human Capital and Institutional Barriers**

Technology adoption is only as successful as the people and institutions that manage it. Nigeria faces a critical shortage of specialized expertise.

- *Skills Gap:* There is a significant deficit in local talent proficiency in AI/ML model development, data engineering, and advanced power system control, particularly in the context of digital twin maintenance and operation. This necessitates a massive, coordinated effort in technical education and training.
- *Institutional Resistance and Inertia:* The transition from a manual, reactive operational model to an automated, data-driven one requires a fundamental cultural shift within the utility companies. Resistance to change, coupled with regulatory inertia, and the fear of job displacement can slow down the adoption of new technologies.
- *Governance and Corruption:* The high rate of NTL is not purely a technical problem, but a governance issue rooted in corruption and poor enforcement. Without addressing the institutional failures that enable electricity theft, even the most sophisticated AI detection systems will struggle to achieve their full impact. AI-driven NTL detection must be paired with robust legal and enforcement mechanisms.

### **5.3 Cybersecurity and Data Privacy**

The digitalization of the grid inherently increases the attack surface, making cybersecurity a paramount concern.

- *Increased Vulnerability:* A fully interconnected Smart Grid, managed by AI and DTs, presents a single, high-value target for cyberattacks, which could lead to widespread blackouts or data manipulation. The risk of a coordinated attack on the national grid is significantly higher in a digitalized environment.
- *Lack of a Unified Framework:* Nigeria currently lacks a comprehensive, unified cybersecurity framework specifically tailored for critical national energy infrastructure that mandates security standards for all DisCos and the TCN.
- *Data Privacy:* The collection of granular consumption data for NTL detection and DSM raises significant data privacy concerns for consumers, necessitating clear regulatory guidelines and robust anonymization protocols. The framework must balance the need for data-driven optimization with the protection of consumer rights.

### **5.4 Policy Recommendations for Adoption**

To successfully harness the potential of AI and DT, a multi-pronged policy and investment strategy is required:

## **6. CONCLUSION AND FUTURE WORK**

The energy crisis in Nigeria, characterized by chronic instability, high losses, and a vast energy access deficit, demands a radical, technologically advanced solution. This review has demonstrated that the synergistic application of Artificial Intelligence and Digital Twin technologies offers a viable and necessary pathway to transform the Nigerian power sector

from a fragile, loss-ridden system into a resilient, efficient, and financially sustainable Smart Grid.

**Table 2.** Policy Recommendation for Adoption

Recommendation Area	Specific Policy Action	Expected Outcome
Data Foundation	Mandate universal, standardized smart metering across all DisCos within a five-year timeframe.	Provide real-time, high-quality data necessary for AI/DT implementation and NTL reduction.
Infrastructure	Prioritize investment in a dedicated, secure fiber-optic communication backbone for the TCN and critical substations.	Ensure reliable, high-bandwidth data transfer for real-time DT operation and grid control.
Human Capital	Establish specialized AI/Smart Grid training centers in partnership with local universities and international technology providers.	Develop the local expertise required to build, deploy, and maintain advanced digital systems.
Governance	Implement a transparent, performance-based regulatory framework that rewards DisCos for NTL reduction and grid stability improvements.	Align financial incentives with technological adoption and combat institutional resistance.
Cybersecurity	Develop and enforce a national cybersecurity standard for the energy sector, including mandatory penetration testing and incident response protocols.	Protect the digitalized grid from cyber threats and ensure system resilience.

AI-driven load forecasting and NTL detection directly address the core operational and financial failures of the current system, promising to stabilize the grid and recover billions in lost revenue. Simultaneously, Digital Twin technology provides the essential platform for simulating complex grid dynamics, optimizing the life-cycle management of aging assets, and safely planning the integration of decentralized energy resources.

However, the transition is not purely a technical one. Success hinges on a foundational commitment to data standardization, massive investment in communication infrastructure, and a concerted effort to build local human capital and overcome institutional inertia. The policy recommendations outlined herein provide a phased roadmap for the Nigerian government and utility companies to move beyond incremental fixes toward a comprehensive digital transformation.

Future research should focus on the development of AI-driven microgrid control systems tailored for the Nigerian context, the socio-economic impact analysis of NTL reduction on consumer behavior, and the creation of low-cost, open-source DT frameworks specifically designed for data-scarce developing economies. By embracing this digital revolution, Nigeria can not only solve its chronic power problems but also establish a scalable model for energy sector modernization across the developing 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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# RETROFITTING MECHANICAL, ELECTRICAL AND PLUMBING (MEP) SYSTEMS IN EXISTING BUILDINGS: CHALLENGES, STRATEGIES AND PATHWAYS TO SUSTAINABLE PERFORMANCE

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## ABSTRACT

*Retrofitting Mechanical, Electrical, and Plumbing (MEP) systems in existing buildings has become increasingly essential as global priorities shift toward sustainability, energy efficiency, and improved occupant well-being. Many older buildings were constructed before the advent of modern energy codes and advanced building technologies, leading to high energy consumption, poor indoor environmental quality, and functional limitations. This paper examines the challenges associated with MEP retrofitting—specifically obsolete infrastructure, spatial constraints, regulatory compliance, financial limitations, and occupant disruption—and identifies practical strategies to overcome them. The study further evaluates the significance of building audits, system compatibility assessments, and energy-efficiency analyses as essential foundations for retrofit planning. Drawing from contemporary research and international best practices, the literature review synthesizes insights on energy-efficient HVAC upgrades, electrical modernization, plumbing optimization, building automation systems (BAS), and the role of digital tools such as Building Information Modeling (BIM). The paper concludes by emphasizing the importance of integrated design, stakeholder collaboration, and long-term planning to achieve sustainable, resilient, and high-performance building environments.*

## 1. INTRODUCTION

The Significance of Retrofitting MEP Systems in Buildings As global emphasis on sustainability and environmental awareness intensifies, the retrofitting of MEP (Mechanical, Electrical, and Plumbing) systems in existing structures has gained paramount importance. MEP systems are essential for the operation, efficiency, and comfort of buildings, including critical components such as heating, ventilation, air conditioning, electrical systems, and plumbing. What is the significance of retrofitting MEP systems? The majority of existing structures were built without the contemporary energy efficiency criteria currently anticipated.

Obsolete MEP systems may lead to heightened energy usage, subpar indoor air quality, and restricted control over comfort settings. Furthermore, traditional systems may lack the capability to accommodate the demands of contemporary technologies and innovations in building management systems. Retrofitting MEP systems provides a transformational remedy to these issues. Upgrading and optimising mechanical, electrical, and plumbing systems enables building owners and managers to realise substantial energy savings, diminish greenhouse gas emissions, and improve tenant comfort and well-being. Furthermore, retrofitting can extend a building's lifespan, enhance its market value, and ensure compliance with contemporary sustainability programs and legislation. Nonetheless, retrofitting MEP systems presents some obstacles. It necessitates meticulous planning, proficiency, and an extensive comprehension of the current building framework and systems. Each facility poses distinct obstacles, including restricted space for equipment installation, compatibility concerns with antiquated components, and the necessity to reduce disturbance to continuing activities during the retrofitting process. This blog post will examine the issues encountered in retrofitting MEP systems in buildings and offer practical strategies to address them. By comprehending these problems and using effective techniques, building owners, engineers, and contractors can successfully rehabilitate structures and establish sustainable, efficient, and comfortable environments for occupants. Let us explore and reveal the strategies for effective MEP system retrofitting.

## **2. LITERATURE SURVEY**

Retrofitting MEP systems is widely acknowledged as a critical strategy for reducing energy consumption and improving the operational performance of existing buildings, which globally account for nearly 40% of total energy use and 30% of greenhouse gas emissions (IEA, 2021). Older buildings often operate with inefficient mechanical and electrical infrastructure that predates contemporary sustainability standards. Studies show that upgrading HVAC, lighting, electrical distribution, and plumbing systems can reduce building energy consumption by 20–50% depending on the building type and retrofit depth (US DOE, 2019).

A major difficulty in retrofitting is the incompatibility between modern high-efficiency technologies and a building's originally installed systems. Older facilities often have limited electrical capacity, deteriorated plumbing, and outdated HVAC components (Zhao et al., 2019). These constraints increase both technical complexity and project costs, requiring detailed system assessments and phased integration strategies. Researchers emphasize the need for thorough pre-retrofit audits to identify deteriorated wiring, asbestos-containing materials, load limitations, and corrosion in plumbing networks (Ma et al., 2012).

Spatial limitations present frequent barriers in retrofitting efforts. Many existing buildings lack adequate room for new ductwork, central air-handling units, or upgraded electrical distribution systems. According to Choi and Song (2020), retrofits in compact commercial buildings require innovative solutions such as modular chillers, decentralized ventilation systems, and high-efficiency ductless equipment. BIM modeling has emerged as a critical tool for analyzing routing conflicts, particularly in dense mechanical rooms (Ghaffarianhoseini et al., 2017).

Ensuring compliance with updated codes—such as ASHRAE standards, local electrical codes, and plumbing regulations—can significantly influence project scope. Older structures often fail to meet requirements for emergency egress lighting, ventilation, electrical grounding, and fire safety (Aksamija, 2015). Bringing aging systems into compliance may require major structural modifications. Scholars recommend early consultation with authorities having jurisdiction (AHJs) to minimize delays and avoid costly redesigns (Chen & Luo, 2020).

MEP upgrades can significantly impact building occupants through noise, dust, temporary service interruptions, and restricted access. Studies show that stakeholder communication and phased construction reduce disruption and enhance user satisfaction (Dwaikat & Ali, 2018). Strategies such as nighttime construction, temporary services, and modular prefabrication can minimize operational downtime (Kamel & Memari, 2019).

A comprehensive building audit is the foundation of successful MEP retrofits. Audits typically include energy modeling, physical inspections, thermographic imaging, indoor air quality assessments, and review of historical maintenance data (Rysanek & Choudhary, 2013). Energy audits help identify performance gaps, including air leakage, HVAC inefficiencies, oversized systems, and wasteful lighting practices.

ASHRAE's Level I–III audit methodology is widely adopted internationally for determining retrofit pathways (ASHRAE, 2018). Research shows that Level III audits, which incorporate extensive measurements and simulations, significantly improve retrofit accuracy and cost-benefit projections (Ma et al., 2012).

Common inefficiencies identified in existing buildings include:

- Oversized HVAC equipment operating at partial loads (Katipamula & Brambley, 2005)
- Aging electrical distribution systems with high line losses (Ahn et al., 2019)
- Water leaks and inefficient plumbing fixtures causing wastage (Matos et al., 2017)
- Lack of automation, leading to poorly controlled operations (Costa et al., 2019)

Building performance simulations—using tools such as EnergyPlus and eQuest—enable comparison of various retrofit scenarios, forecasting savings and payback periods.

Compatibility challenges arise when integrating high-efficiency systems into old infrastructure. For instance, variable refrigerant flow (VRF) systems may require strengthening structural supports, while LED lighting retrofits may require rewiring due to differences in ballast requirements (Zhang et al., 2020). Researchers recommend phased hybrid systems, where older equipment remains operational during integration of newer components (Ma et al., 2012).

Effective retrofit strategies prioritize energy efficiency, occupant comfort, and long-term adaptability. Research identifies the following high-impact retrofit measures:

- High-efficiency heat pumps and VRF systems (Torres-Rivas et al., 2019)
- LED lighting with occupancy and daylight sensors (Dubois & Blomsterberg, 2011)
- Building automation systems (BAS) with IoT-enabled controls (Jin et al., 2018)
- Low-flow plumbing fixtures and greywater recycling (Matos et al., 2017)
- Demand-controlled ventilation for enhanced air quality and reduced energy use (Peffer et al., 2010)

Advanced tools such as BIM, GIS-based facility modeling, and digital twins support precise planning, clash detection, and lifecycle cost analysis (Ghaffarianhoseini et al., 2017).

### **3. COMPREHENDING THE DIFFICULTIES ASSOCIATED WITH RETROFITTING MEP SYSTEMS**

Retrofitting MEP (Mechanical, Electrical, and Plumbing) systems in older structures can pose numerous issues. Retrofitting necessitates meticulous planning and consideration of existing infrastructure, building requirements, and budgetary limitations, in contrast to new construction projects. Comprehending these problems is crucial for devising effective solutions for

successful retrofits.

A significant problem encountered in retrofitting is the incorporation of new MEP systems into the pre-existing building configuration. The building's structural limitations, including restricted space and antiquated infrastructure, can present considerable challenges. This necessitates careful coordination and collaboration among architects, engineers, and contractors to devise novel solutions that enhance space utilisation while maintaining the functioning and efficiency of the MEP systems.

A further hurdle involves maneuvering through the intricacies of building laws and regulations. Retrofitting frequently entails enhancing obsolete systems to comply with contemporary building standards, which may differ based on location and building type. A comprehensive evaluation of the current systems is essential to identify areas requiring compliance with regulations. This may include supplementary expenses and alterations to the building's framework, which must be meticulously strategised to reduce disturbances and enhance compliance.

Financial limitations significantly influence the retrofitting of MEP systems. Retrofitting projects generally incur higher costs than new construction due to the necessity for substantial changes and enhancements to existing systems. It is imperative to develop a thorough budget that accounts for both initial expenditures and ongoing maintenance and operational costs. Prioritising investments according to the building's requirements and anticipated returns can facilitate smart resource allocation and guarantee a sustainable retrofit. \

Moreover, the collaboration across several MEP disciplines can provide a challenge during retrofitting. The integration of mechanical, electrical, and plumbing systems requires effective communication and collaboration among diverse professions. Creating integrated systems that function synergistically necessitates a profound comprehension of the interrelations and possible conflicts among different fields. Effective communication channels and regular coordination meetings are essential for swiftly addressing difficulties and ensuring the seamless execution of the retrofit project.

In conclusion, retrofitting MEP systems in existing structures entails distinct problems. Comprehending and tackling these problems is essential for a successful retrofit initiative. By meticulously evaluating the current building infrastructure, adhering to building regulations, managing financial limitations, and promoting efficient collaboration, it is feasible to surmount these challenges and revitalise older edifices through novel MEP retrofit solutions.

### **3.1 Obsolete infrastructure and systems**

Obsolete infrastructure and systems present considerable obstacles in retrofitting MEP (Mechanical, Electrical, and Plumbing) systems within buildings. Numerous historic edifices were erected prior to the emergence of contemporary technologies and energy-efficient methodologies, rendering it imperative to rectify the antiquated infrastructure to enhance usefulness, efficiency, and sustainability.

A principal difficulty associated with obsolete infrastructure is its incompatibility with contemporary MEP systems. The current electrical, HVAC, and plumbing systems may lack compatibility with contemporary equipment and technologies. This may result in inefficiencies, elevated energy usage, and increased maintenance expenses. Retrofitting these systems necessitates meticulous planning and assessment to guarantee that the new components

can function properly with the existing infrastructure.

A further problem is the constrained space for the installation of upgraded MEP systems. Historic structures frequently possess limited spaces, complicating the integration of modern equipment and technology without compromising the building's architectural integrity. Retrofitting solutions must consider spatial constraints and devise inventive methods to optimise the available area while preserving usefulness and aesthetics.

Moreover, obsolete systems may fail to comply with contemporary code requirements and safety regulations. This may present possible dangers and obligations for property owners and occupants. Retrofitting MEP systems offers a means to resolve compliance difficulties and guarantee that the building adheres to requisite standards and certifications. Upgrading electrical wiring, upgrading fire prevention systems, and boosting ventilation and air filtering are critical for assuring safety and occupant welfare.

A thorough evaluation of the building's MEP requirements is essential to address the issues presented by obsolete infrastructure and systems. This entails performing a comprehensive assessment of the current systems, pinpointing opportunities for enhancement, and formulating a retrofitting strategy that meets the building's specific needs. Engaging with seasoned MEP engineers and consultants facilitates the creation of tailored solutions that maximise energy efficiency, boost indoor air quality, and improve overall building performance.

In conclusion, retrofitting MEP systems in buildings with antiquated infrastructure necessitates meticulous evaluation of compatibility, spatial constraints, and regulatory compliance. By confronting these difficulties directly and applying new solutions, property owners may rejuvenate existing buildings, enhance functioning, and establish sustainable environments for the future.

### **3.2. Constrained area for apparatus and ducting**

Retrofitting mechanical, electrical, and plumbing (MEP) systems in existing structures sometimes presents the significant obstacle of constrained space for equipment and ducting. Numerous older edifices were not conceived with contemporary MEP systems in consideration, resulting in confined areas that complicate the installation or enhancement of these vital systems.

Constrained space can present numerous challenges. Initially, there may be insufficient space to install new equipment or augment current systems. This is especially difficult for HVAC (heating, ventilation, and air conditioning) systems, which necessitate substantial equipment including air handling units, chillers, and ducting.

A further concern is the insufficient room for running ducting. In retrofit projects, it is frequently essential to devise innovative solutions for routing ducts through existing structures, which may be constrained by spatial limitations. This may entail employing unconventional methods or integrating innovative technologies such as cloth air dispersion systems that occupy less physical space.

Moreover, constrained space can affect maintenance and accessibility. When systems are confined to restricted places, it becomes increasingly difficult for personnel to do normal maintenance or resolve any emerging concerns. This may result in prolonged downtime and elevated maintenance expenses over time.

To address these challenges, it is essential to involve seasoned MEP engineers and contractors who specialise in retrofit projects. They possess the proficiency to devise effective solutions that optimise the utilisation of available space. This may entail employing small machinery, investigating alternative duct routing strategies, or contemplating modular or prefabricated systems that may be erected on location.

Moreover, employing sophisticated technologies such as Building Information Modelling (BIM) facilitates the visualisation of spatial limitations and enhances design optimisation prior to installation. BIM facilitates clash detection and coordination among diverse MEP disciplines, guaranteeing that systems can be accommodated within constrained spaces without conflicts.

In conclusion, managing constrained space for equipment and ductwork is a prevalent difficulty when retrofitting MEP systems. Nonetheless, with appropriate skills, innovative thinking, and the application of current technology, it is feasible to surmount these problems and effectively rejuvenate buildings with efficient and contemporary MEP systems.

### **3.3. Compliance with construction codes and requirements**

Compliance with building rules and regulations is essential for retrofitting MEP (Mechanical, Electrical, and Plumbing) systems in existing structures. While striving to enhance the energy efficiency and functionality of these structures, it is imperative that any renovations and upgrades adhere to the requisite norms and laws established by local authorities.

The initial phase in this process is performing a comprehensive evaluation of the current building's compliance status. This entails examining the pertinent building laws and regulations to comprehend the requirements that the retrofitting project must fulfil. Engaging with seasoned professionals, including architects, engineers, and contractors, who possess expertise in these codes and laws is imperative.

A common problem in retrofitting projects is that older buildings may not comply with contemporary norms and requirements. This may create challenges in attaining compliance without substantial alterations or concessions. Retrofitting solutions must balance enhancements to the MEP systems with the preservation of the building's structural integrity and historical significance.

To address these difficulties, it is essential to collaborate closely with building officials and authorities having jurisdiction (AHJs). Maintaining transparent contact and soliciting their counsel during the retrofitting process helps guarantee the acquisition of all requisite licenses and approvals. Engaging with seasoned experts possessing extensive knowledge of local norms and regulations helps facilitate the navigation of potential challenges and guarantee compliance.

Furthermore, it is essential to remain informed about any modifications or revisions in construction codes and regulations. Regulatory standards may change over time, and it is crucial to stay informed of these developments to ensure the retrofitting project remains compliant throughout its duration.

In conclusion, compliance with building rules and regulations is essential when retrofitting MEP systems in existing structures. By meticulously evaluating compliance mandates,

consulting with experts, and liaising with building authorities, retrofitting initiatives can surmount obstacles and adeptly manoeuvre within the regulatory framework. This compliance guarantees the safety and operation of the retrofitted structure while promoting sustainable and energy-efficient solutions advantageous to both occupants and the environment.

### **3.4 Interference to occupants during the retrofitting procedure**

A significant problem encountered during the retrofitting of MEP (Mechanical, Electrical, and Plumbing) systems in older structures is the possible interruption to tenants. During the retrofitting of a building, construction activities typically result in noise, dust, and temporary disturbances to its routine operations.

Disruption of occupants might pose a considerable issue, particularly in commercial structures where enterprises function and in residential edifices where individuals dwell. The discomfort resulting from the retrofitting procedure may engender unhappiness among occupants and adversely affect productivity in commercial environments.

To address this difficulty, it is essential to meticulously plan and communicate with residents during the retrofitting process. Presented below are several strategies to mitigate disruption:

- a. Formulate a comprehensive timetable: A meticulously crafted calendar delineating the various phases of the retrofitting procedure might assist tenants in anticipating any disruptions. This enables people to implement requisite modifications to their professional or residential settings.
- b. Deliver consistent updates: It is imperative to keep occupants apprised of the retrofitting project's progress. Consistent communication via newsletters, emails, or meetings can facilitate expectation management and resolve any enquiries or issues they may possess.
- c. Adopt a phased construction strategy: Rather of closing the entire facility for retrofitting, consider employing a phased methodology. This enables sections of the building to stay functional while work is conducted in other areas. This can mitigate interruption and inconvenience to inhabitants.
- d. Temporary relocation provisions: In instances where the retrofitting procedure is substantial and disruptive, offering temporary relocation options for inhabitants may be contemplated. This may entail locating alternate premises for enterprises or providing temporary housing for inhabitants.
- e. Employ noise and dust mitigation strategies: Implementing strategies to manage noise and dust during building operations is essential for reducing interruption. This may involve the implementation of barriers, soundproofing materials, and dust control systems to enhance occupant comfort.

By addressing occupant concerns and proactively managing the retrofitting process, disturbance can be minimised, facilitating a smoother transition and eventually ensuring a successful retrofit of the MEP systems in the building.

## **4. EVALUATING THE CURRENT MEP SYSTEMS**

Prior to initiating a retrofitting project for MEP (Mechanical, Electrical, and Plumbing) systems, it is essential to conduct a comprehensive evaluation of the current systems. This evaluation will yield critical information into the condition, efficiency, and operation of the building's MEP systems.

Commencing the assessment procedure necessitates the collection of all pertinent documentation concerning the MEP systems. This may encompass as-built drawings,

operational and maintenance manuals, equipment specifications, and maintenance records. These documents will provide a basis for comprehending the original design intent and any alterations or enhancements implemented over the years.

A thorough site survey must be performed to visually assess the MEP systems and detect any apparent indications of deterioration, corrosion, leaks, or inefficiencies. This examination must encompass all sections of the structure, including mechanical rooms, electrical distribution panels, HVAC units, plumbing fixtures, and fire prevention systems.

Alongside the visual examination, it is imperative to conduct diagnostic tests and measurements to evaluate the functioning of the MEP systems. This may entail doing energy audits, airflow assessments, electrical load evaluations, water flow examinations, and thermographic imaging to detect energy losses, imbalances, or malfunctions.

It is essential to consult facility managers, tenants, and maintenance staff during the assessment process to obtain their thoughts and feedback on any persistent difficulties or limitations of the current MEP systems. This crucial information aids in comprehending the daily obstacles encountered and offers a comprehensive perspective on the deficiencies that must be rectified during the retrofitting procedure.

By meticulously evaluating the current MEP systems, building owners and project teams can acquire a detailed grasp of the facility's infrastructure and recognise potential issues and constraints. This evaluation is essential for formulating efficient retrofitting strategies and executing requisite renovations to improve the building's functionality, energy efficiency, and overall performance.

#### **4.1 Performing a comprehensive building audit and evaluation**

In the retrofitting of MEP (Mechanical, Electrical, and Plumbing) systems in existing structures, performing a comprehensive building audit and assessment is an essential initial step. This procedure includes a thorough assessment of the building's existing MEP systems to pinpoint areas for enhancement or modernisation.

The audit commences with a thorough analysis of the building's designs and current MEP plans. This aids in comprehending the configuration and design of the systems, as well as recognising any potential obstacles that may emerge during the retrofitting process. Furthermore, it is imperative to collect historical data on energy consumption, maintenance logs, and occupant comfort evaluations to provide insights into the system's efficacy and potential issues.

During the on-site evaluation, a team of specialists will conduct a physical examination of the MEP systems, encompassing HVAC (Heating, Ventilation, and Air Conditioning), electrical distribution, lighting, plumbing, and fire prevention systems. They will check the equipment's condition, identify indicators of deterioration, and evaluate the overall efficiency and usefulness of the systems.

Through this thorough analysis, the team can pinpoint areas for enhancing energy efficiency, potential dangers or bottlenecks within the systems, and chances for optimisation. They will also consider any building codes or regulatory mandates that must be handled during the retrofitting procedure.

The building audit and assessment yield essential data for formulating a complete retrofitting

strategy. It assists in prioritising problems necessitating urgent attention, defining the scope of work, estimating the price and timing, and aligning retrofitting aims with the building owner's goals.

In conclusion, doing a comprehensive building audit and evaluation is a crucial stage in the retrofitting of MEP systems. It establishes a robust basis for recognising issues, assessing the current system's performance, and formulating efficient solutions to restore the building's infrastructure while guaranteeing energy efficiency, occupant comfort, and regulatory compliance.

#### **4.2 Recognising inefficiencies and opportunities for enhancement**

Recognising inefficiencies and opportunities for enhancement is an essential phase in the retrofitting of MEP (Mechanical, Electrical, and Plumbing) systems within structures. It is imperative to do a comprehensive evaluation of the current systems to identify any vulnerabilities, obsolete technologies, or energy inefficiencies that require remediation.

A principal issue in this identification method is the intricacy of MEP systems. The systems are interlinked, and any inefficiency in a single component can propagate throughout the entire system. Consequently, it is essential to perform a thorough assessment of each system and its components, including HVAC (Heating, Ventilation, and Air Conditioning), lighting, electrical distribution, and plumbing.

Building owners and retrofitting professionals can utilise several approaches to discover inefficiencies. An effective strategy involves doing energy audits or assessments. These audits entail assessing energy consumption patterns, scrutinising utility bills, and employing sophisticated tools and technology to quantify energy usage. This aids in pinpointing areas of energy wastage, like obsolete equipment, ineffective insulation, or inadequate control mechanisms.

Alongside energy audits, including tenants and facility managers in the process is essential. They can offer significant insights into daily operations and possible issues. Input from occupants concerning comfort, air quality, and illumination might assist in pinpointing areas for enhancement.

An additional useful technique is to utilise data and building management systems (BMS). A Building Management System (BMS) may gather and assess real-time data from several systems, offering critical insights into energy use, equipment efficiency, and future optimisation opportunities. This data-centric methodology facilitates the accurate identification of inefficiencies and aids in prioritising retrofitting initiatives.

Moreover, collaborating with seasoned MEP professionals and consultants can significantly assist in pinpointing inefficiencies and formulating efficient remedies. Their proficiency and understanding of industry best practices allow them to perform comprehensive evaluations, detect any problems, and recommend suitable retrofitting solutions.

Identifying inefficiencies and areas for enhancement is a vital step in upgrading MEP systems. By conducting energy audits, analysing data, collaborating with tenants and professionals, and utilising advanced technology, building owners can acquire critical insights and formulate effective strategies to improve the performance and efficiency of their buildings.

### **4.3 Assessing the congruence of novel systems with current infrastructure**

Evaluating the compatibility of new MEP (Mechanical, Electrical, and Plumbing) systems with existing infrastructure is a critical step in retrofitting these systems in established structures. It is imperative to guarantee that the new systems interface effortlessly with the legacy components, without inducing any disruptions or undermining overall performance.

The compatibility study commences with a thorough evaluation of the current MEP systems. This entails assessing the age, condition, and functionality of the existing infrastructure. Comprehending the advantages and constraints of current systems aids in recognising possible obstacles and devising appropriate solutions.

The design team must meticulously evaluate the specifications and requirements of the new MEP systems. This entails evaluating issues like capacity, energy efficiency, sustainability, and adherence to codes. Compatibility transcends physical components; it also includes operational aspects, control systems, and automation.

During the assessment process, potential conflicts and limitations may emerge due to spatial restrictions, structural factors, or financial restraints. It is imperative to tackle these difficulties preemptively to prevent expensive rework or concessions in functioning.

A comprehensive feasibility analysis and meticulous coordination among the diverse disciplines engaged in the retrofitting process is one method to guarantee compatibility. This interdisciplinary method facilitates a thorough evaluation of the compatibility of new systems with the current infrastructure. It necessitates intensive collaboration among architects, engineers, contractors, and other stakeholders to evaluate potential implications and devise appropriate solutions.

When existing infrastructure presents constraints, novel methods like modular installation or phased implementation may be utilised. These solutions facilitate the integration of new technologies while minimising disruptions and optimising productivity.

Moreover, utilising modern technologies such as Building Information Modelling (BIM) can significantly assist in assessing compatibility. BIM facilitates the visualisation and simulation of the retrofitting process, allowing for the preemptive identification of collisions and disputes. It optimises the coordination process, minimises errors, and enables the seamless integration of new systems with the current infrastructure.

In conclusion, assessing the compatibility of new systems with existing infrastructure is essential for retrofitting MEP systems in buildings. Through comprehensive evaluations, interdisciplinary cooperation, and the utilisation of sophisticated technologies, difficulties can be surmounted, and successful solutions can be executed. This guarantees a successful retrofitting process that improves the performance, efficiency, and sustainability of the structure.

### **4.4 Developing retrofit strategies**

Developing retrofit solutions for MEP systems can be intricate and demanding. It necessitates meticulous evaluation of the current building configuration, structural constraints, and the intended performance objectives. Retrofitting MEP systems entails enhancing and altering the mechanical, electrical, and plumbing systems of a pre-existing structure to augment energy efficiency, occupant comfort, and overall performance.

A primary problem in developing retrofit solutions is guaranteeing compatibility with the current infrastructure. This entails performing a comprehensive evaluation of the building's existing MEP systems, pinpointing prospective enhancements, and assessing the viability of incorporating new technologies or components. The design team must meticulously assess issues including spatial limitations, load limits, and system interdependencies to formulate appropriate retrofit techniques.

An additional crucial element of developing retrofit solutions is enhancing energy efficiency. This may entail the adoption of energy-efficient technologies, including high-efficiency HVAC systems, LED lighting, and sophisticated control systems. The design team must evaluate energy consumption trends, do energy audits, and employ modelling tools to assess possible energy savings and identify the most economical alternatives.

Moreover, retrofitting MEP systems frequently necessitates inventive design strategies to address architectural and structural limitations. The design team must collaborate closely with architects, structural engineers, and other stakeholders to devise innovative solutions that harmoniously align with the building's aesthetics and structural integrity. This may entail utilising space-efficient apparatus, adaptable piping and ducting systems, and novel routing alternatives to reduce disturbances throughout the retrofitting procedure.

Moreover, it is essential to contemplate future adaptability and scalability. Creating retrofit solutions that facilitate future upgrades or expansions guarantees that the MEP systems can adapt to evolving requirements and technological progress without substantial interruptions or expensive alterations. This progressive strategy ensures the building's longevity and optimises the return on investment for the retrofit initiative.

## **5. CONCLUSION**

Retrofitting MEP systems is essential for transforming outdated buildings into energy-efficient, sustainable, and high-performance environments. Despite challenges—such as obsolete infrastructure, spatial limitations, compliance barriers, and potential disruption to occupants—strategic planning and modern engineering solutions can significantly enhance building functionality. Comprehensive building audits, system compatibility assessments, and interdisciplinary collaboration form the backbone of effective retrofit planning. Emerging technologies such as building automation systems, BIM, and advanced HVAC systems further support decision-making and improve retrofit outcomes. Ultimately, successful MEP retrofitting extends the lifespan of existing structures, reduces operational costs, enhances occupant comfort, and contributes to global sustainability objectives.

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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 COMPREHENSIVE PROCESS TO EFFICIENT SOLAR PHOTOVOLTAIC SYSTEM ENERGY MANAGEMENT AND MAINTENANCE

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### Abstract

*The expansion of photovoltaic systems emphasizes the crucial requirement for effective operations and maintenance, drawing insights from advanced maintenance approaches evident in the wind industry. This review systematically explores the existing literature on the management of photovoltaic operation and maintenance. Through the integration of bibliometric analysis and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, 186 articles are selected for further comprehensive review.*

*The selected articles are examined and categorized into four interconnected research domains: maintenance strategies, performance indicators, degradation modeling, and maintenance optimization and planning. The presented analysis underscores the importance of integrating maintenance strategies to enhance system effectiveness. It also emphasizes the necessity of a systematic approach that integrates reliability assessment with economic and technical considerations to optimize maintenance planning and enhance system availability and resource efficiency. This aligns with the Sustainable Development Goals for affordable, reliable, and sustainable energy, while also ensuring grid security. Furthermore, the study identifies gaps and proposes avenues for improvement, recommending a shift towards prognostic approaches and the advancement of predictive maintenance in photovoltaic systems. Key suggestions also include customizing metrics for large installations, implementing adaptive protocols that move away from traditional component-centric scheduling, and using reinforcement learning to prioritize risk and optimize long-term performance. Compared to previous reviews focusing on specific maintenance elements, this work provides a broader perspective by incorporating planning and organizational factors into the maintenance discussion.*

### 1. INTRODUCTION

The rapid global expansion of solar photovoltaic (PV) technology has transformed it from a niche energy solution into a mainstream component of modern electricity systems. Declining costs, improved module efficiencies, and strengthening policy commitments to decarbonization

have accelerated adoption across residential, commercial, and industrial applications (IEA, 2024; Fraunhofer ISE, 2022). In many developing regions—including Sub-Saharan Africa—solar PV provides an especially compelling alternative to conventional fossil-fuel generators due to its modularity, low operating costs, and capacity to support energy access for underserved households and small businesses (Keisang et al., 2021; REN21, 2022). However, while the installation of PV systems continues to increase, significant gaps persist in users' understanding of system operation, maintenance requirements, and long-term performance optimization.

Effective operation and maintenance (O&M) practices are indispensable for ensuring that PV systems meet expected energy-yield targets, minimize financial losses, and operate safely throughout their service life (Bosman et al., 2020; Hernández-Callejo et al., 2019). Research shows that inadequate or inconsistent maintenance can lead to accelerated degradation, increased downtime, safety hazards, and reduced return on investment (Aghaei et al., 2022; Koester et al., 2022). While large utility-scale plants often employ professional O&M service providers, owners of small and medium-sized enterprises (SMEs), households, and microgrid operators frequently lack access to technical guidance and practical tools needed to ensure proper system upkeep. As highlighted by Márquez (2022), many existing studies examine discrete aspects of PV maintenance—such as fault diagnosis, soiling, or degradation patterns—yet few offer an integrated, user-oriented approach that combines operational, technical, safety, and financial considerations.

The aims of this paper respond directly to these gaps by providing clear, practical, and accessible guidance on solar PV system operation, maintenance, safety, and performance monitoring. First, it seeks to equip SME owners and system operators with the knowledge required to improve energy efficiency, reduce operational costs, and extend system lifespan (Feldman et al., 2023). Second, it offers step-by-step maintenance procedures, troubleshooting methods, and advice on when professional technical assistance is warranted, drawing on established industry standards and research evidence (Walker, 2018; Livera et al., 2022). Third, the paper targets general users—including households and small businesses—by demystifying the functional principles of PV systems and promoting informed decision-making related to performance monitoring and safety (Navid et al., 2021). Finally, the paper emphasizes the importance of adhering to safety protocols, regulatory requirements, and international best practices to safeguard users and prevent accidents (Høiaas et al., 2022; Hernández-Callejo et al., 2019).

In addition to addressing technical and operational competencies, the paper highlights broader motivations for improved PV O&M, including cost savings, system reliability, and environmental sustainability. By empowering users to undertake routine maintenance and identify emerging issues early, unnecessary expenses—such as premature component failures, inefficient energy use, or preventable repairs—can be significantly reduced (Conceicao et al., 2022; Peinado-Gonzalo et al., 2020). Aligning user practices with established O&M standards also supports the long-term goals of renewable-energy adoption, including emission reduction, improved energy access, and compliance with national and international benchmarks (REN21, 2022; IEA, 2024). In this regard, the paper also serves as a crucial resource for technicians, system owners, microgrid operators, and other stakeholders who require structured, actionable, and safety-focused guidance for managing PV installations.

By integrating technical explanations, practical procedures, diagnostic tools, safety requirements, and maintenance frameworks, this paper contributes to the growing body of literature on PV system O&M. It offers a holistic and user-centered approach that prioritizes system reliability, energy performance, safety, and longevity—dimensions that are essential

for maximizing the value of solar PV investments across diverse user groups and system applications.

## **1. 2. LITERATURE REVIEW**

The literature reveals a wealth of review studies on topics related to PV O&M, as well as bibliometric studies within the solar PV research domain. Table 1 classifies the literature reviews on PV O&M- related subjects based on their scope and also categorizes the different bibliometric studies in the field of solar energy. Several review articles have conducted comprehensive investigations on monitoring and fault diagnosis techniques in the field of PV systems. Specifically, Høiaas et al. [2022] reviewed optics-based tools for large-scale PV module inspection, including fault classification and evaluations of infrared thermography and luminescence imaging technologies. These techniques are pivotal in aiding O&M operators in accurately identifying faults in PV plants. Similarly, Jaen-Cuellar et al.[2022] investigated faults in solar PV and wind power systems, analyzing their causes and impact on efficiency and maintenance costs. The study emphasized the growing utilization of data-driven techniques, such as machine learning (ML), for fault detection and diagnosis. Investigating failure and degradation modes in PV systems has also received considerable attention in the literature. Peinado Gonzalo et al.[2020] analyzed failure and degradation mechanisms in PV modules, emphasizing the identification of root causes and prevention techniques for issues such as soiling, snow deposition, corrosion, cracks, and hot spots. The study emphasized preventive maintenance techniques such as surface modifications, coatings, and fatigue analysis. Another study by Hernández-Callejo et al. [2019] discussed critical components, design factors, and O&M of PV systems, addressing energy control mechanisms, module degradation, and the influence of meteorological factors. Mitigation techniques such as uniform cooling were studied, and operational risk management was utilized to identify risks associated with electric current, fire hazards, natural events, and human factors.

Some reviews have focused on the effect of dust and soiling on PV panels and investigated various cleaning methods for enhanced performance. Conceicao et al. [2022] examined the advancement of soiling research in solar energy, covering soiling characterization, modeling, and various cleaning techniques and their influence on O&M costs. Other studies have explored various maintenance schemes for PV systems. In their study, Keisang et al. [2021] investigated O&M strategies in PV microgrid systems, including corrective, preventive, and predictive maintenance. The study focused on O&M challenges and solutions in PV microgrids in Sub-Saharan Africa, highlighting the importance of decentralized PV generation in addressing electricity access and poverty. Considerable focus has also been directed towards predictive maintenance and energy forecasting methods. For example, Ramirez-Vergara et al. [2022] looked into predictive maintenance models as an economical option for solar PV systems. The article assessed forecasting methods for critical factors such as solar irradiance and temperature, particularly highlighting the potential of ML models.

It is evident that the O&M management of PV systems lacks comprehensive research that addresses the broader challenges and complexities of maintenance. As mentioned by Márquez [2022], a comprehensive examination of maintenance management issues in solar energy systems is needed. Although Keisang et al. [2021] recognized the

importance of developing a maintenance itinerary and engaging stakeholders, their emphasis was primarily on managerial guidelines for O&M approaches. Furthermore, their assessment criteria overlooked essential technical system-related parameters, such as equipment reliability, failure rates, maintenance costs, and system availability. A successful maintenance program seeks to minimize failures, maximize production uptime, and reduce production loss through timely interventions. Once a maintenance strategy is determined, the focus shifts to scheduling, presenting an optimization challenge to ensure continuous and reliable operation of the PV system. However, there is a lack of comprehensive guidance on how to effectively coordinate the timing and sequencing of maintenance interventions and strategically integrate them within the broader operational context of a PV system. In addition, the effectiveness of O&M programs relies on the inclusion of factors such as staff coordination, required spare parts, and logistics and supply chain management, which have not received sufficient attention despite being crucial for techniques.

Madsuha et al. [2021] analyzed solar research in Indonesia, covering semiconductors, simulation, and integration of technology and regulation. In addition, a comprehensive analysis conducted by David et al. [2020] observed the evolving trends in PV energy management, discovering crucial aspects such as demand management, consumer behavior, and module materials. It is evident that the application of bibliometrics in the context of PV systems O&M management remains underexplored. The existing literature lacks detailed thematic descriptions of the management and planning of maintenance tasks, which are essential to ensure optimal performance. This gap calls for a more thorough and systematic analysis, tracking the evolving trends, and exploring key themes in PV O&M beyond the conventional domains. Embracing a holistic approach to O&M management enables a comprehensive understanding of the technical, operational, and financial elements involved. This ensures that maintenance practices are not limited to isolated tasks, but are integrated into a cohesive and efficient system.

### **3. THE PURPOSES OF O&M FOR PV SYSTEMS**

Operations and maintenance (O&M) is critical for keeping solar photovoltaic systems performing at their best over their lifetime. While we often think of solar as a “set it and forget it” technology, proper maintenance ensures systems meet production targets, maintain warranties, and operate safely.

Proper O&M serves several key purposes for PV systems:

- a. Maximizes system availability and minimizes downtime
- b. Helps meet expected financial and energy production targets
- c. Maintains equipment warranties
- d. Ensures system safety and manages liability
- e. Provides data to inform future design decisions

The solar industry increasingly recognizes that O&M shouldn't be an afterthought—it should be factored into system design and budgeting from the beginning. This approach ultimately saves money by improving reliability and reducing maintenance costs. PV maintenance requires a balanced approach between prevention and reaction. Preventative maintenance provides the foundation of system care—scheduled, predictable work that maintains health and meets warranty requirements. Like dental hygiene, it's about addressing small issues before they become major problems. Reactive maintenance, though sometimes unavoidable, typically

costs more and creates unplanned disruptions.

The most effective O&M strategies emphasize prevention while maintaining readiness for quick reaction when necessary. Even with rigorous preventative protocols, external factors like severe weather, wildlife damage, or equipment failures will occasionally demand immediate attention. The goal isn't eliminating reactive maintenance entirely, but rather minimizing its frequency through thoughtful prevention, which ultimately improves system reliability while reducing lifetime maintenance costs.

There are three critical diagnostic tools that should be in every solar technician's toolkit: They are:

(a) *I-V Curve Tracers*: I-V curve tracers measure the relationship between current and voltage in a PV circuit, providing insight into how modules are performing. This tool allows technicians to:

- Test PV array performance independent of the inverter
- Establish baseline data at commissioning
- Verify performance against manufacturer specifications
- Troubleshoot specific issues with modules or strings

A key advantage is the ability to detect problems that wouldn't show up using basic multimeter tests. For example, a module with a third of its cells bypassed due to damage would show normal open-circuit voltage and short-circuit current readings with a multimeter, but the I-V curve would reveal the issue through characteristic "humps" or "notches."

(b) *Thermal Imaging*: Thermal cameras have become an essential tool for O&M providers due to their efficiency and ease of use. They detect temperature differences that indicate potential issues in both PV modules and electrical equipment. Two main applications include:

- a. *Aerial thermal imaging* efficiently evaluates large arrays to identify modules or strings with issues. Drones or aircraft equipped with thermal cameras can quickly scan entire systems to find anomalies.
- b. *Handheld thermal imaging* is ideal for examining electrical equipment like combiners, inverters, and terminations, as well as for targeted troubleshooting of specific modules.

Common issues that thermal imaging can detect include non-operating strings or modules, bypass diode failures, cell hotspots, loose electrical connections, and blown fuses. It's important to remember that thermal imaging shows symptoms rather than causes—additional troubleshooting is typically needed to determine the underlying problem.

(c) *Insulation Resistance Testing*: Insulation resistance testing measures how well insulation prevents leakage of electrical current. This testing:

- Verifies conductor integrity during commissioning
- Establishes baseline data for future comparisons
- Helps locate ground faults during troubleshooting

For PV systems specifically, insulation resistance testing can identify which module or section of wiring has a ground fault. By systematically measuring voltages between the

array's conductors and ground, technicians can pinpoint fault locations with remarkable precision.

#### **4. PRACTICAL GUIDELINES FOR FIELD TESTING**

PV maintenance requires a balanced approach between prevention and reaction. Preventative maintenance provides the foundation of system care—scheduled, predictable work that maintains health and meets warranty requirements. Like dental hygiene, it's about addressing small issues before they become major problems. Reactive maintenance, though sometimes unavoidable, typically costs more and creates unplanned disruptions.

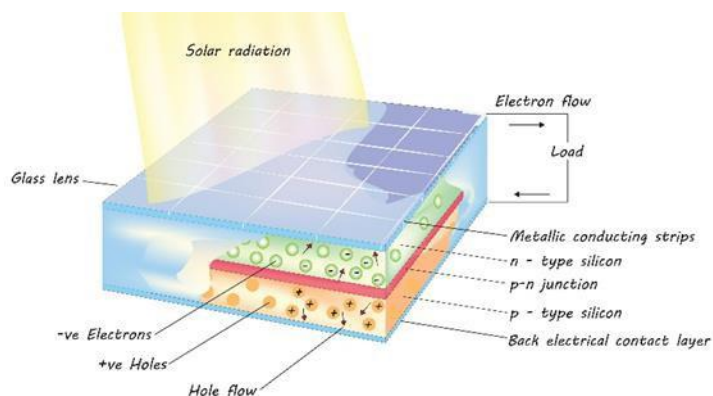
The most effective O&M strategies emphasize prevention while maintaining readiness for quick reaction when necessary. Even with rigorous preventative protocols, external factors like severe weather, wildlife damage, or equipment failures will occasionally demand immediate attention. The goal isn't eliminating reactive maintenance entirely, but rather minimizing its frequency through thoughtful prevention, which ultimately improves system reliability while reducing lifetime maintenance costs. Effective solar O&M requires both proper planning and the right diagnostic tools. I-V curve tracers, thermal cameras, and insulation resistance testers provide complementary data that helps technicians identify and resolve issues efficiently.

As the solar industry continues to mature, comprehensive O&M strategies become increasingly important to ensure systems perform reliably over their 25+ year lifespan. Investing in proper maintenance practices and diagnostic tools ultimately protects the long-term value of these renewable energy assets.

### **5.0 OVERVIEW OF SOLAR PV SYSTEM**

#### **5.1 The Scope of Solar PV Systems Covered / What are the fundamentals of PV Systems**

Photovoltaic (PV) solar energy conversion is a process that utilizes semiconductor materials, which are predominantly composed of silicon, to transform sunlight into electrical energy. The fundamental principle behind solar PV technology is the photovoltaic effect. Electrons within the semiconductor material of the solar cells are energized when sunlight strikes the material, generating an electrical current.



**Figure 1.** Photovoltaic Effect © KKT Madhusanka | Dreamstime

Solar panels are constructed from solar cells as their fundamental components. In most cases, these cells are constructed from silicon, a readily available material with advantageous semiconductor characteristics. Solar cells can be monocrystalline,

polycrystalline, or thin film, each with different efficiencies and costs.

*Monocrystalline Solar Cells:* Made from a single crystal of silicon, these cells are highly efficient and recognizable by their uniform black color and rounded edges. They are ideal for spaces with high energy demands and limited area.

*Polycrystalline Solar Cells:* Constructed from multiple silicon fragments melted together, these cells have a distinct blue, speckled appearance. They are less efficient than monocrystalline cells but more cost-effective.

*Thin-Film Solar Cells:* Composed of photovoltaic material layers on a substrate, these are lightweight and flexible. They are less efficient but excellent for large-scale or portable applications. Solar cells are assembled into larger units known as solar panels or modules. These panels are typically what you see on rooftops or in solar farms.

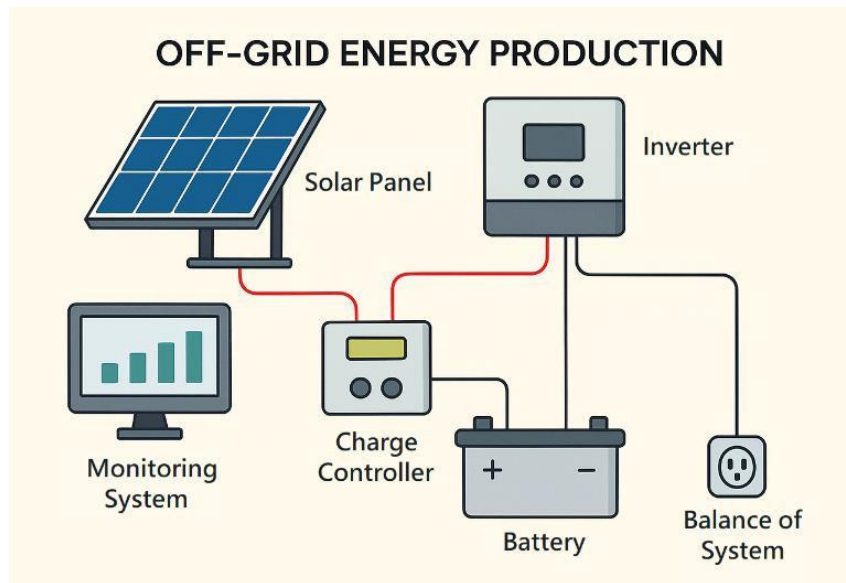


**Figure 2.** Types of solar cells – monocrystalline at the bottom, polycrystalline at the top. Source: <https://amplussolar.com/blog/complete-guide-about-types-of-solar-panels/>

## **5.2 Components of Solar PV Systems**

Regardless of the size and location of an installation, the basic components needed to guarantee a correct and safely functioning Solar PV system are the same.

Additional components can be included to increase the performance and efficiency of the overall system.



**Figure 3.** Off-grid solar power system with battery storage. OpenAi (2025). ChatGPT (May 27 Version)

**Table 1.** Components of Solar PV Systems

Fundamental components	Description
Solar Panels (PV Modules)	<i>Function:</i> Capture sunlight and convert it into direct current (DC) electricity. <i>Types:</i> Monocrystalline, polycrystalline, and thin-film solar panels, each with different efficiencies and cost. Typically installed on rooftops, ground mounts, or solar farms.
Inverters	<i>Function:</i> Convert DC electricity generated by the solar panels into alternating current (AC) electricity. It is essential for the usability of solar energy in standard electrical systems and for feeding electricity into the grid. <i>Types:</i> String inverters, microinverters, and hybrid inverters.
Mounting Systems	<i>Function:</i> Securely hold solar panels in place. It needs to be robust and weather-resistant and may need to be angled for optimal sun exposure. <i>Types:</i> Fixed mounts, tracking mounts, and ground-mounted
Electrical Components	Include wiring, fuses, circuit breakers, and disconnect switches. <i>Function:</i> Ensure safe operation and connectivity of the solar PV system and protect against electrical surges and faults.
Balance of System	All other components that are required to ensure the proper functioning of the solar PV system, such as grounding equipment, conduits, junction boxes, etc.
Additional components	Description

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Batteries	<p><i>Function:</i> Store excess electricity produced by solar panels for use when there is no sunlight (e.g., at night or during cloudy days). <i>Types:</i> Lead-acid, lithium-ion, and flow batteries, with varying capacities, lifespans, and costs. <i>Important:</i> Particularly important for off-grid systems or grid-tied systems with a self-consumption focus.</p>
Charge Controllers	<p><i>Function:</i> Regulate the voltage and current coming from the solar panels to the batteries, preventing overcharging and damage to the batteries. <i>Types:</i> Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT), with MPPT being more efficient. <i>Important:</i> fundamental in case batteries are connected to the PV system.</p>
Monitoring Systems	<p><i>Function:</i> Track the performance of the solar PV system, including energy production, system health, and efficiency. <i>Types:</i> Onsite and remote monitoring systems, often accessible via smartphone apps or web interfaces.</p>
Grid Interconnection Equipment (grid- tied)	<p>Includes specific types of inverters and safety equipment that meet grid standards and regulations. <i>Function:</i> Safely and legally connect the solar PV system to the public electricity grid. <i>Important:</i> Needed for PV systems connected to the public grid.</p>

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Each component in a solar PV system *must be carefully selected and integrated* to ensure maximum efficiency, safety, and longevity of the system.

### **5.3 System Layout and Configuration**

Designing a solar PV system involves several key considerations to ensure optimal performance, safety, and efficiency. The form and design of the system can vary considerably depending on factors such as the application (residential, commercial, industrial), location, available space, and unique energy requirements. For instance, residential systems often prioritize aesthetics and space efficiency, utilizing rooftop installations to maximize available area, whereas commercial systems may focus on larger-scale energy production, often employing flat-roof or ground-mounted setups. In industrial applications, high energy demands and robust infrastructure lead to extensive ground-mounted arrays or hybrid systems with backup storage. Location plays a critical role, as areas with high solar irradiance favor optimal panel tilt angles and orientations for maximum sunlight capture, while regions prone to extreme weather require reinforced structures. Available space determines the layout, with limited areas requiring compact, high-efficiency panels, while open spaces allow for expansive installations. Finally, unique energy requirements, such as off-grid or grid-tied systems, influence the inclusion of storage batteries, inverters, and backup systems to meet specific energy reliability and usage patterns.

### **5.4 Solar Panels Arrangement**

Select panels of either monocrystalline, polycrystalline, or thin-film type, considering their efficiency, cost, and space requirements. To fully tap into the potential of an installation,

it is important to consider carefully where those are placed and their inclination angle as both aspects influence the energy ultimately produced under the same weather conditions.

*Orientation and Tilt:* there is no standard value that can be applied to all installations as orientation depends on the geographical location. In the Northern Hemisphere, solar panels are commonly positioned facing south and angled at a degree similar to the latitude of the area to optimize sunlight absorption. Likewise, in the southern hemisphere, panels face North.

*Shading:* Ensuring that there are no barriers such as trees, buildings, or other objects that block sunlight over the sun hours.

## **5.5 Mounting Structure**



**Figure 5.** Mounting Structure

PV systems are mounted on stable structures that secure them fixed in the best possible positioning. The main options are:

1. *Roof-mounted systems* take advantage of the built environment and are typically found in residential or industrial settings. These systems necessitate a robust roof that can support them and hence structure reinforcement may be needed.
2. *Ground-mounted systems* are employed where there is insufficient or inappropriate roof space. Land space is necessary and therefore considerations regarding the environmental impact of the installation should be considered.

It is also possible to include in the installation a tracking system that detects the trajectory of the sun and rotates PVs toward its direction, enhancing efficiency but also leading to an increase of the costs.

## **5.6 Inverter and their placement**

Inverters are fundamental to convert the electricity produced by the PVs and make them suitable for the common house and office appliances. This component can be placed close



**Figure 6.** White inverter for solar cell system

There are several types of inverters:

1. *String inverters*, which manage multiple panels together and are suitable for smaller systems.
2. *Central inverters* are for large commercial systems.
3. *Microinverters*, which are attached to each panel for increased efficiency and monitoring.
4. *Solar Inverter*, typically designed to work directly with solar panels, optimizing energy production using maximum power point tracking (MPPT).
5. *Battery Inverter*, designed to manage and integrate energy storage systems, enabling stored energy to be utilized during power outages or at night.

Additionally, hybrid inverters, or multi-mode inverters, play a crucial role in certain solar photovoltaic (PV) systems. They integrate the features of a conventional solar inverter and a battery inverter allowing for effectively handling energy derived from solar panels, the electrical grid, and battery storage devices.

### **5.7 Battery storage**

Solar energy is an intermittent source as it depends on the presence of sunlight. Batteries allow us to store the energy produced and not directly consumed to use it later when the sun is not present. These are fundamental in case the system is off grid, meaning that it is not connected to the public grid that could compensate for the electricity need when electricity produced by the PV is not available anymore.

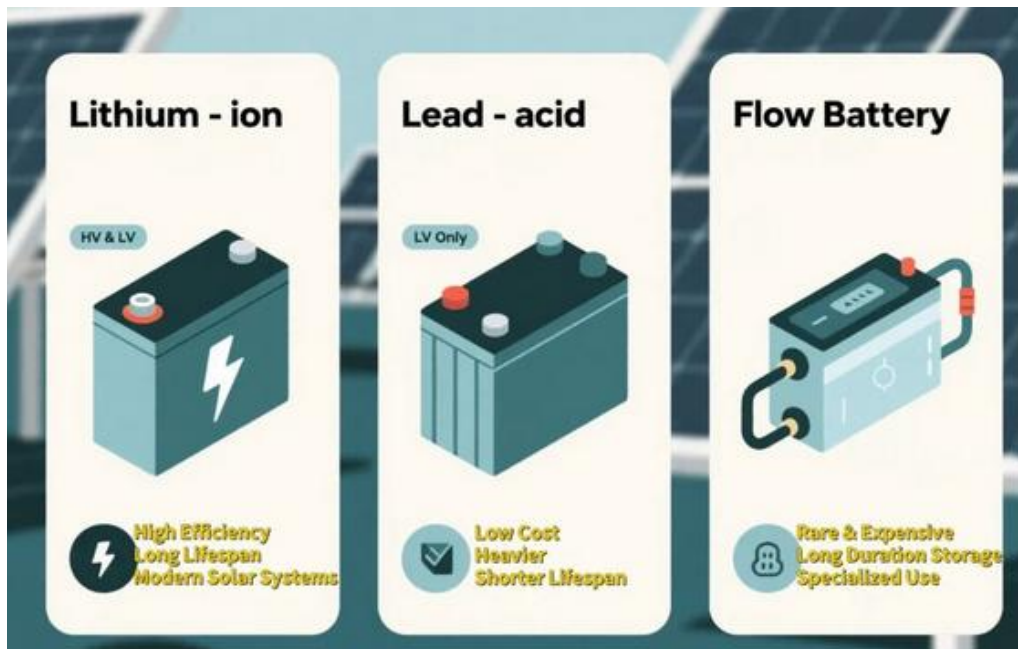


Figure 8. Modern battery for solar systems ©Alexey Arama Dreamstime.com

Some considerations related to the storage are:

1. *Position*: the inverter for easy integration into the system and far from hot places.
2. *Size and Capacity*: The size of the battery storage system is determined based on energy production, the needs and the desired autonomy (how long the system can run without sunlight).
3. *Integration*: Battery storage must be smoothly incorporated with the PV system to enable energy storage and utilization during periods of low solar production.

Batteries are not the only way to store energy. Other options are hydrogen storage, compressed air storage and thermal storage.

## 5.8 Charge Controller

Charge controllers are important to ensure healthy batteries, preventing their degradation due to wrong voltage or overload of energy. Those are usually installed between the solar panels and the batteries. The specific layout and configuration of a solar PV system can vary greatly based on individual requirements and constraints. It's essential to engage with qualified solar professionals to design and install a system that meets the specific needs of the site and the users effectively.

## 6. SAFETY PRECAUTIONS

### 6.1 Personal Protective Equipment (PPE)

The utilization of Personal **Protective Equipment (PPE)** is essential in guaranteeing the safety of persons engaged in the operation and maintenance of Solar Photovoltaic (PV) systems. PV systems incorporate electrical elements and are frequently deployed in open-air settings, presenting diverse hazards. A comprehensive analysis of the essential PPE employed in PV systems is presented in the Table below.

Table 2. Personal Protective Equipment (PPE)

Category	Description
Electrical Insulated Gloves	<i>Purpose:</i> Protect against electric shocks when handling electrical components of the solar PV system. <i>Specification:</i> Should be rated for the specific voltage levels encountered in the system.
Safety Glasses or Goggles	<i>Purpose:</i> Protect the eyes from harmful solar radiation, dust, debris, and accidental splashes of cleaning or maintenance chemicals. <i>Specification:</i> Should have UV protection and be impact resistant.
Hard Hats	<i>Purpose:</i> Protect the head from falling objects, especially when working under or near solar panels installed at height. <i>Specification:</i> Should meet industry safety standards.
Protective Footwear	<i>Purpose:</i> Protect feet from falling objects, sharp edges, and electric shocks. <i>Specification:</i> Should be sturdy, have electrical insulation, and possibly steel toes for enhanced protection.
Sun Protection Gear	<i>Purpose:</i> Protect against prolonged exposure to the sun, which is common during outdoor work. It can include long-sleeved shirts, sun hats, and sunscreen.
Respiratory Protection	<i>Purpose:</i> Protect against inhalation of harmful dust, especially during cleaning or maintenance activities. <i>Specification:</i> Dust masks or more advanced respirators, depending on the level of exposure.
Protective Work Clothing	<i>Purpose:</i> General protection against cuts, abrasions, and other minor injuries. <i>Specification:</i> Durable material, possibly with reinforced areas for additional protection

The selection of PPE should be based on a thorough risk assessment, considering the specific tasks, the environment, and the potential hazards associated with the operation and maintenance of solar PV systems. Regular training on the proper use and maintenance of PPE is also essential to ensure safety.

## **6.2 Electrical safety**

Ensuring electrical safety is of utmost importance when operating and maintaining PV systems. Although these systems are eco-friendly, they require careful management of high-voltage power, which can present significant dangers if mishandled.

Below are essential factors and procedures to guarantee electrical safety:

- a) A comprehensive understanding of PV system constituent parts, including solar panels, inverters, DC/AC converters, batteries (if applicable), and wiring systems. Acquiring this knowledge aids in the recognition of possible dangers. To ensure solid knowledge of electrical principles and becoming acquainted with the PV being used

appropriate training and certifications are necessary for everyone engaged in the installation, operation, or maintenance of PV systems. Moreover, the utilization of Personal Protective Equipment (PPE) presented in the section above is imperative to consistently employ suitable PPE to mitigate the likelihood of electric shock and other forms of harm.

- b) Ensure equipment conformity to national and municipal electrical codes, as well as industry standards established by organizations like the Institute of Electrical and Electronics Engineers (IEEE) or the International Electrotechnical Commission (IEC).
- c) *Set electrical lockout and tagout procedures*: Enforce lockout/tagout protocols to guarantee the safe de-energization of the system during maintenance or repair. This serves as a precautionary measure to avoid unintentional activation of the system.
- d) *Apply safe installation practices*: It is important to make sure that all components are placed according to the guidelines provided by the manufacturer and the electrical codes of the local area. Ensuring proper grounding and bonding is crucial for minimizing the likelihood of electric shock.
- e) *Labelling and Signage*: It is important to mark electrical components with information such as power ratings and warning signs. This helps to alert and remind personnel about potential hazards.
- f) *Be aware of weather-related risks*: It is important to understand that PV systems can produce electrical energy even when the weather is cloudy. Additionally, be aware of the increased risk of electrical hazards during wet or stormy weather.
- g) *Maintenance of battery Safety (for systems with storage)*: If the system incorporates energy storage components, it is crucial to handle and maintain batteries correctly, as they may pose extra risks such as chemical leakage or thermal runaway.
- h) *Schedule periodic maintenance and inspections*: Routinely examine and uphold the PV system to guarantee its optimal functionality. This entails inspecting for impaired cables, insecure linkages, and indications of corrosion.

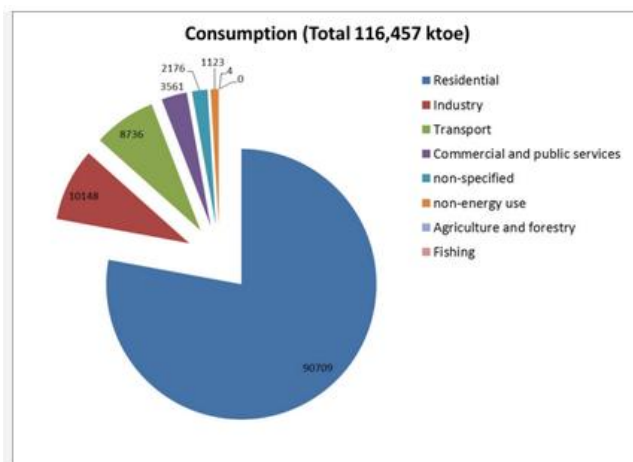
### **6.3 Regular operation procedures**

The routine functioning of solar PV systems generally entails the activities of monitoring, conducting maintenance checks, and assuring optimal system performance. Although solar PV systems typically require minimal maintenance, it is essential to follow regular operational practices to ensure optimal performance and promptly detect any potential problems. Below is a 10 points summary of the standard operating procedures for solar PV systems.

1. *Visual Examination*: Inspect the solar panels for any apparent signs of damage, such as fractures, discolouration, or the accumulation of debris and vegetation. Examine the mounting systems for any indications of looseness or impairment. Make sure that there are no obstacles such as fallen branches or heavy debris on the panels.
2. *Performance Monitoring*: Examine the energy production statistics obtained from the inverter or monitoring system. Analyze the daily production with anticipated performance benchmarks using records and weather conditions. Monitor for any substantial declines in energy generation, as these may indicate potential problems with the solar panels or inverter.



**Figure 9.** Dusty and Weathered Solar Panel Array. Source: <https://cleanenergy4africa.org/solar-energy-and-dust-control/>



**Figure 10.** Nigeria Energy Situation: Source: [https://energypedia.info/wiki/Nigeria\\_Energy\\_Situation](https://energypedia.info/wiki/Nigeria_Energy_Situation)

3. *Inverter inspection:* Ensure proper functioning of the inverter. Typically, inverters are equipped with an indicator light or display panel that provides real-time information about their present functioning state. Pay attention to any atypical sounds emanating from the inverter, since they may suggest internal malfunctions.
4. *Battery systems inspection (if applicable):* verify the charge levels of systems equipped with battery storage and verify that they fall within the recommended range. Observe any indicators or notifications regarding battery functionality.
5. *Connections inspection:* Verify that all electrical connections are firmly attached and there are no indications of excessive heat, such as discoloration or wire melting. It is advisable to approach this task with caution. The assistance of a professional is highly recommended, as it has inherent risks.
6. *Solar Panel Cleaning:* Periodically clean solar panels when they accumulate excessive dust, bird droppings, or other debris to ensure optimal efficiency. Utilize suitable cleaning techniques, such as employing gentle brushes and mild soapy water, while refraining from using abrasive substances or harsh chemicals.

7. *Shading inspection:* Monitor the panels for any newly occurring shading problems, which may be attributed to the growth of trees, recent construction activities, or other obstacles. The presence of shading can greatly diminish the effectiveness of a solar PV system.
8. *Environmental factors:* Take into consideration the prevailing meteorological conditions. Following severe weather phenomena such as storms or significant rainfall, it may be imperative to conduct supplementary inspections and sanitation procedures.
9. *Documentation:* Keep a detailed record of daily performance metrics, inspections, and all maintenance tasks. This record is extremely valuable for monitoring and evaluating the functioning of the system over some time, as well as for recognizing any patterns or problems that may arise.
10. *Professional Maintenance Services:* Ensure to regularly schedule professional inspections and maintenance services, since certain areas of system check-up and maintenance necessitate specialized expertise and equipment.

#### **6.4 Routine Maintenance Practice**

The execution of regular maintenance procedures is critical in ensuring the optimal operation and durability of solar PV systems. This will also ensure its maximal performance and fasten the return on investment. By dividing these responsibilities into distinct subsections, a comprehensive strategy for system maintenance is achieved. The classification of these maintenance duties is described in more detail below.



*Figure 11: Solar PV maintenance. Source: <https://rkwindmast.com/c/can-you-power-wash-solar-panels.html>*

#### **6.5 PVs cleaning and inspection scheduled**

*Frequency:* Typically, every 6–12 months, more often in dusty or bird-prone areas.

##### *6.5.1 Cleaning:*

- *Method:* Use soft brushes or sponges and mild soapy water. Avoid abrasive materials and high-pressure water sprays.
- *Focus Areas:* Remove debris, dirt, and bird droppings from solar panels.

## **6.6 Inspection:**

- *Visual Checks:* Look for cracks, discoloration, or delamination in panels.
- *Mounting and Racking Systems:* Ensure all bolts and supports are secure.
- *Shading:* Check for new shading issues due to tree growth or new constructions.
- *Grounding and Bonding:* Ensure these are intact for safety and system performance.

## **6.7 Inverter Maintenance**

- *Frequency:* Monthly (minimum), Detailed Checks Quarterly
- *Visual Inspection:* Check for any error messages on the display, signs of overheating, or physical damage. Inspect mounting integrity and ensure the inverter is secure and not vibrating.
- *Performance Monitoring:* Verify status indicators (LEDs) and LCD/online display for any warning/error codes and confirm proper DC input voltage and AC output voltage levels for any unusual drops or inconsistencies.
- *Ventilation:* Ensure the inverter is well-ventilated and free from dust, moisture and debris.
- *Firmware Updates:* Keep the inverter's firmware updated as per manufacturer's recommendations.

## **6.8 Battery Maintenance (for systems with storage)**

- *Frequency:* Monthly, with Detailed Capacity Testing Annually

### *Inspection:*

- *Performance Monitoring:* measure and record individual battery voltages and string voltages.
- *Room Inspection:* Confirm battery room ventilation, temperature, and absence of leaks or fire hazards

As mentioned in Table 1, the two main types of batteries used in PV systems are lead-acid and lithium-ion. Each of these two types requires different precautions:

### *Lead-Acid Batteries:*

- *Water Levels:* Regularly check and top up water levels in flooded lead-acid batteries.
- *Terminal Checks:* Clean and tighten battery terminals to prevent corrosion and ensure good connections.
- *State of Charge:* Regular monitoring to avoid overcharging or deep discharging.

### *Lithium-Ion Batteries:*

- *Temperature Monitoring:* Ensure they are operating within the recommended temperature range.
- *Software:* Keep battery management system software up to date.
- *Visual Inspection:* Check for any signs of swelling or damage.

### *Electrical Connections Check*

- *Frequency:* Every 6 Months (or quarterly in high-humidity, dusty, or corrosive environments) When verifying the electrical connection, it is important to check the following:
  - *Tightness of Connections:* Ensure all electrical connections are tight and secure and perform torque checks on terminal screws and cable lugs
  - *Corrosion Inspection:* Look for any signs of corrosion on terminals and connections.
  - *Temperature Inspection:* Check for any signs of overheating (discoloration, melting insulation).

- *Wiring Inspection:* Check for any signs of fraying, rodent damage, or wear on the wiring and conduct insulation resistance testing (especially after major rain/dust events).
- *Safety Checks:* Ensure all safety switches, circuit breakers, surge protection devices and disconnects are functioning properly.

## 7. TROUBLESHOOTING COMMON ISSUES

### 7.1 Diagnostic Steps for Common Problems

**Table 3.** Common issues

Issue Category	Symptoms	Diagnostic Steps	Suggested Actions
Reduced Power Output	Lower-than-usual energy production	<ol style="list-style-type: none"> <li>1. Inspect for shading or obstructions.</li> <li>2. Check for dirt or debris on panels.</li> <li>3. Monitor the inverter for error messages.</li> <li>4. Review historical performance data.</li> </ol>	<ul style="list-style-type: none"> <li>• Clean panels</li> <li>• remove obstructions.</li> <li>• reset, or troubleshoot inverter.</li> </ul>
Inverter Issues	Error messages, no power output	<ol style="list-style-type: none"> <li>1. Refer to the manual for error codes.</li> <li>2. Perform power cycling.</li> <li>3. Check the inverter’s ventilation.</li> </ol>	<ul style="list-style-type: none"> <li>• Reset the inverter.</li> <li>• ensure proper ventilation.</li> <li>• contact a professional if the error persists.</li> </ul>
Battery-Related Issues	Poor charging, battery not holding charge	<ol style="list-style-type: none"> <li>1. Check charge levels.</li> <li>2. Inspect connections.</li> <li>3. For lead-acid, check water levels.</li> </ol>	<ul style="list-style-type: none"> <li>• Tighten connections.</li> <li>• refill water (if applicable)</li> <li>• professional battery check.</li> </ul>
Panel Damage	Visible damage, reduced panel output	<ol style="list-style-type: none"> <li>1. Visual inspection.</li> <li>2. Check the electrical output with a multimeter.</li> </ol>	<ul style="list-style-type: none"> <li>• Replace damaged panels.</li> <li>• professional assessment.</li> </ul>

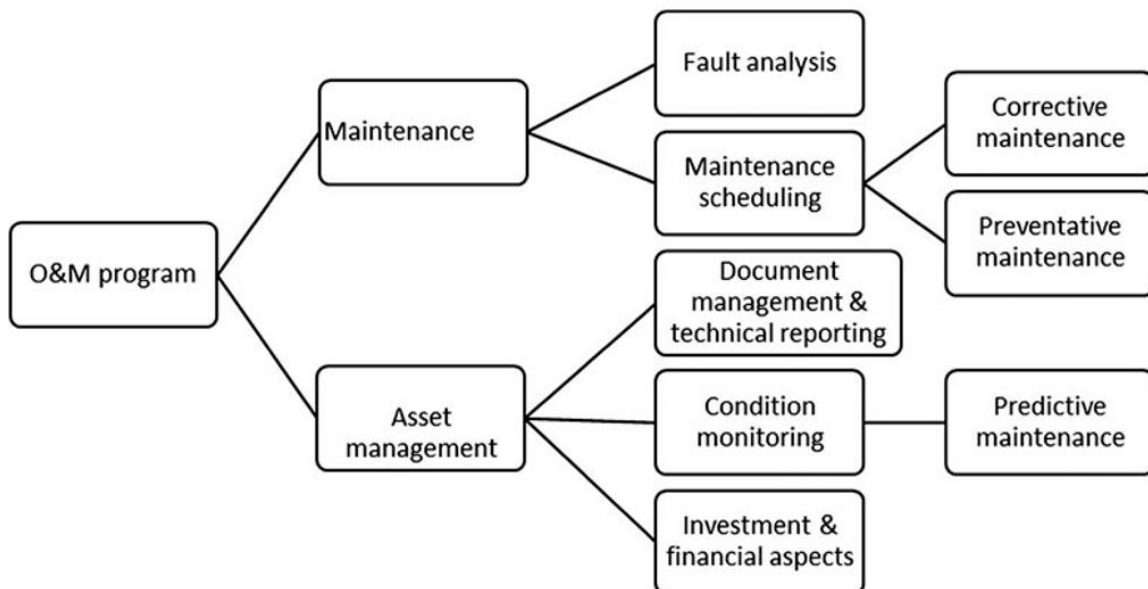
### When to Contact a Professional Technician

**Table 4.** Assistance by Professional Technician

Issue	Description	Professional Assistance Needed When
Physical Damage	Cracks, discolouration, or other damage to components	Damage is significant and affects system performance.
Electrical Concerns	Wiring or connection issues	Problems are complex or high-risk (e.g., inverter failure).
Battery Issues	Problems with charging or battery health	Issues persist despite basic troubleshooting, or if safety risk is present.
Safety Risks	Any issue requiring work at heights or with high voltage	Safety risks are involved, or specialized knowledge is required.

## 8. DISCUSSION

The increase in the implementation of solar PV systems has indirectly led to improvements in maintenance methods. Researchers have created advanced technologies and tools for enhanced and precise system fault diagnostics, troubleshooting, and timely remedial responses by incorporating features for document management, technical reporting, fault analysis, maintenance scheduling, and financial reporting (Gilabert and Arnaiz 2006; Efthymiou et al., 2012; Abbassi et al., 2015). Operations and maintenance, being a highly technical facet of solar photovoltaic technology, depends on the system's size, specific design, and contextual location. These complexities result in variations in maintenance implementation methods across diverse locations and distinct installation needs. A maintenance management framework is essential to implement remedial measures promptly to prevent downtime and prolong the overall system's service life. Figure 6 delineates the essential components for establishing a comprehensive maintenance program.



**Figure 6.** Diagram illustrating the principal components of a maintenance program (Eltawil and Zhao 2010; Hirsch et al., 2018).

Mgonja, C. T. and Saidi, H. conducted a study on off-grid solar photovoltaic systems in public facilities (Mgonja and Saidi 2017), emphasising maintenance management systems to assess the effectiveness of their deployment. This assessment utilised a case study methodology to present a model that underscores the necessity for collaborative efforts among all pertinent stakeholders engaged in SPV systems from the planning to the disposal phase. The proposed model seeks to enhance field maintenance practices through the active engagement of stakeholders in promoting a proactive maintenance culture, emphasising that the delayed implementation of a maintenance management scheme during the initial project phase adversely affects long-term sustainability. The British Standards Institution (BSI, 2010) emphasises that continuous and comprehensive planning is essential for the successful implementation of solar PV installations, from project conception through construction,

supervision, inspections, and commissioning duties. The fragmentation of responsibility directly contributes to the efficacy of the operation and maintenance of solar photovoltaic microgrids. The workflow, encompassing the early identification of impending failure and the swift deployment of maintenance personnel equipped with appropriate tools and spare parts, necessitates a collaborative effort among asset managers, plant operators, and field technicians (Averbukh et al., 2013; Tejwani et al., 2014). The schematic illustrates that the operator is only responsible for operations and maintenance, while the Asset Manager oversees the managerial and financial aspects of the microgrid operations (Palit and Sarangi 2014). This paradigm ensures sustainability through the accountability it fosters. Frameworks for Implementing the Operation and Maintenance Program SPV plants, being capital-intensive projects, necessitate effective management to address risks and uncertainties, and crucially, require an individual accountable for fulfilling the project objectives, whether economically based or focused on energy yield security (C 2010; Gonzalo et al., 2020).

The problematic and defective operational circumstances frequently experienced by solar PV fleets are particularly concerning. In the pursuit of enhanced system dependability and long-term sustainability in solar PV systems, an appropriate operational model must be selected. These models exist to guarantee the effective enforcement and execution of the existing O&M strategy while assessing and analysing criteria for success or failure. Operations and maintenance (O&M) can be conducted via various alternatives, including third-party O&M companies or in-house teams, known as maintenance management models (Bosman et al., 2020; Solar Power Europe [SPE] 2018).

Table 3 illustrates that each option possesses distinct advantages and disadvantages, necessitating a judicious decision in the selection of the approach to plant operation, as it will significantly influence subsequent positive or negative repercussions. A decision-making dilemma arises including risk exposure, labour, initial and subsequent costs, quality control, and intellectual capital, necessitating clear and decisive resolution. For example, when an organisation possesses existing O&M-related assets such as skilled personnel, hardware, software, and infrastructure, it may be prudent to use an in-house O&M delivery model to leverage these resources. Outsourcing operations and maintenance is perceived as a cost-saving measure; however, it can lead to complications when the contractor sacrifices quality by utilising inferior or substandard components, adversely affecting overall system performance. A setback may also arise from the installer's bias in notifying the owner of system malfunctions or failures, as this may reflect poorly on their workmanship (installation and design). Furthermore, issues may arise if the installers cease operations, thereby nullifying any post-installation services, including possible warranty claims.

**TABLE 3.** Different models for handling operation and maintenance requirements.

O&M execution model (Epri 2010)	
In-house	Third party
<b>Description</b>	
In this model, the company and or institution owning or hosting the solar PV system is in charge of ensuring optimal performance and smooth operation and takes care of any maintenance needs.	Also termed as outsourced to an external contractor, who is charge of the ensuring the clients needs for reliable electricity supply without interruption is met. The contractor carries out any maintenance needs and any system upkeep activities necessary, including warranty claims.
<b>Advantages</b>	
Better Vicinity on personnel\Equipment Issue.	Lower Upfront Costs, Greater Flexibility.
Improved Quality Control.	Lower Upfront risks.
Ability to leverage existing utility assets.	Less Drain on Utility Labor Force
Workforce training.	
Company has command of solar PV O&M process	
<b>Disadvantages</b>	
Higher upfront costs	Lack of involvement means to knowledge or skills transfer.
Increased risk	Cost may be overinflated
Workforce knowledge\resource ramp up	Dependent on Outsourced Contractors

The intricacies of SPV microgrids, as highlighted in the preceding paragraphs, require that the operations and maintenance of the installations be managed by qualified professionals. This will guarantee the system undergoes judicious administration and fulfils expectations by mitigating risks and uncertainties. The proficient professionals function as both operations and maintenance practitioners, employed by the clients. Their responsibility is to collect data on the current performance and operations of the installations, conduct requisite analysis, diagnosis, troubleshooting, and maintenance on the SPV microgrid. The involvement of expatriates in executing the O&M operations can occur through two methods: In-house or Third-party models, each possessing distinct advantages and disadvantages as highlighted in Table 3. Nevertheless, due to the differing aims and resources, the decision rests with the system owner, guided by the project development team, with the primary aim of safeguarding the capital investment. The decision hinges on the system owner's perspective about the installation and application; for example, a commercial SPV microgrid within an industry possessing an existing maintenance team may prefer a Hybrid model. This innovative method for managing operations and maintenance involves an agreement between the system owner and the solar service firm to undergo a transitional phase during which training and knowledge transfer occur to the utility or organization's personnel. This concept significantly benefits system owners by reducing the entire lifecycle cost of Solar PV installations, particularly for extended contracts with third-

party organisations.

## **9. CONCLUSION AND GENERAL RECOMMENDATIONS**

Solar photovoltaic (SPV) technology is rapidly advancing in both development and implementation, propelled by declining levelized costs of power and supportive governmental policies such as feed-in tariffs. Although solar PV microgrids are inherently lower-risk systems than traditional power generating methods, they face distinct hazards related to financial, operational, and technical factors. In contrast to conventional PV systems, the reliability, safety, and efficiency of SPV microgrids are enhanced by the incorporation of additional protective devices, power conditioning, and modulation electronics. Furthermore, the distribution lines serving remote customers and the intricacies of interconnection networks, exemplified by relevant microgrid topologies such as radial, ring, and tree architectures, contribute to the demands for monitoring, inspection, troubleshooting, and repair. Consequently, a comprehensive approach to Operations and Maintenance (O&M) and a suitable framework to demonstrate its connection to the fundamental success of solar photovoltaic systems is essential. This encourages stakeholders to develop and refine systems design, operational strategies, and maintenance planning and execution methods to guarantee optimal system availability, dependability, safety, effectiveness, and efficiency.

Comprehending the diverse configurations, control architectures, and operational modes in SPV microgrids is essential for analysing the maintenance needs of these systems. Furthermore, many obstacles arise in the functioning of SPVM, contingent upon installation site, component design, and system optimisation objectives. Finally, a definitive evaluation and assessment framework for the maintenance program is essential, encompassing critical metrics for system utilisation, as well as baseline parameters for comparative analysis and performance evaluation. Maintenance is a perpetual endeavour, particularly in the evolving domain of SPV microgrids; therefore, an Operations and Maintenance (O&M) program must be adaptable if it fails to achieve established objectives.

### **9.1 General Recommendations**

The following recommendations are noted in this article:

- *Documentation:* Keep detailed records of all maintenance activities.
- *Professional Inspection:* At least once a year, have a professional technician inspect and service the system.
- *Safety First:* Always prioritize safety, especially when working with electrical components or at heights.

Regular maintenance is crucial for optimizing the efficiency, ensuring safety, and prolonging the lifespan of solar PV systems. Certain operations can be managed by the system owner, however, duties related to electrical components should be performed by competent personnel. Routine maintenance not only extends the lifespan of the system but also guarantees that it functions at its highest level of efficiency, resulting in the most

## **9.2 Conclusions**

The conclusions arrived at in this paper include:

- a. To maintain quality control and safety standards, it is important that only qualified personnel work on PV installations. The authors suggest minimum skill and knowledge guidelines for PV technicians.
- b. Safety is a serious concern when servicing PV installations. Early PV systems often had maximum system voltages less than 50 Vdc, but 1,000 Vdc systems are now allowed by code in commercial and large-scale installations.
- c. Qualified personnel should always work in teams of two people when working on live equipment, and there should always be at least two qualified persons trained in cardiopulmonary resuscitation on the jobsite.
- d. Not all installations have appropriate signage, and qualified persons must be trained to recognize potential hazards with or without signage present.
- e. System uptime and availability is a key objective of O&M, and inverters that are offline can have a dramatic negative impact on the ROI of a PV system.
- f. Low power production also impacts ROI, and O&M personnel need effective strategies for identifying and correcting problems quickly.

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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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## LEVERAGING MOBILE TECHNOLOGY TO ENHANCE FOOD HYGIENE AND ENERGY ACCESS

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### Abstract

*This study assessed the impact of a mobile phone-based educational intervention on food hygiene knowledge, practices, and energy use among street food vendors in Ibarapa Central Local Government Area, Oyo State, Nigeria. A quasi-experimental design involving 200 vendors was conducted over 12 weeks using structured questionnaires and direct field observations before and after the intervention. Post-intervention results revealed statistically significant improvements in food hygiene knowledge, practices, and attitudes. Mean knowledge scores increased from 33.0% to 66.0% ( $t = 12.41$ ,  $p < 0.001$ ), while awareness of foodborne illness rose from 32.0% to 72.0% ( $\chi^2 = 28.6$ ,  $p < 0.001$ ). Hygienic practices improved markedly: covering food on display increased from 35.0% to 79.0% ( $\chi^2 = 42.7$ ,  $p < 0.001$ ), and separation of raw and cooked food from 56.5% to 77.0% ( $\chi^2 = 18.6$ ,  $p < 0.001$ ). Attitude scores rose from 67.7% to 89.2% ( $t = 11.36$ ,  $p < 0.001$ ), indicating stronger motivation toward safe food handling.*

*Observation confirmed behavioural changes in soap availability which improved from 26.0% to 74.0%, and proper waste disposal from 18.0% to 54.0% ( $p < 0.001$ ). Energy access results showed reduced weekly spoilage losses from ₦4,200 to ₦2,300 ( $Z = -6.78$ ,  $p < 0.001$ ) and higher willingness to adopt solar refrigeration (54.0% to 81.0%,  $\chi^2 = 25.3$ ,  $p < 0.001$ ). The findings suggest that mobile technology is a cost-effective tool for enhancing food safety and promoting energy resilience in rural Nigeria which can improve public health and reduce postharvest losses.*

### I. INTRODUCTION

Street-vended foods constitute an integral component of food systems across sub-Saharan Africa, particularly in low- and middle-income countries where they provide affordable,

accessible, and culturally preferred meals to millions of consumers daily (Madaki and Bavorova, 2019). In Nigeria, street food vending serves as both a vital source of livelihood and a significant contributor to urban and rural food security. The sector is largely dominated by women and characterized by low entry barriers, informal regulation, and heavy reliance on ready-to-eat foods (Omemu and Aderoju, 2008). While the benefits of this informal food economy are evident, food safety risks remain a persistent public health concern.

The World Health Organization (WHO) estimates that unsafe food causes more than 600 million illnesses and 420,000 deaths annually, with Africa bearing the highest per-capita burden of foodborne diseases (WHO, 2015). Pathogens such as *Salmonella* spp., *Escherichia coli*, and *Staphylococcus aureus* have been frequently isolated from street-vended foods in Nigeria and other African countries, underscoring the vulnerability of informal food systems (Omemu and Aderoju, 2008; Nijhawan *et al.*, 2022). Beyond health implications, unsafe food practices contribute to significant economic losses, particularly for small-scale vendors who already operate on minimal profit margins.

Studies in Nigeria consistently reveal low levels of knowledge and unsafe hygiene practices among street food vendors. Omemu and Aderoju (2008) reported that only a minority of vendors in Abeokuta demonstrated adequate food hygiene knowledge, while Madaki and Bavorova (2019) observed similar gaps among food handlers in Bauchi State. Factors such as low literacy, lack of structured training, poor access to potable water, and inadequate storage infrastructure contribute to unsafe food handling. These challenges highlight the need for innovative, low-cost, and contextually adaptable interventions to improve food hygiene among informal vendors.

Mobile health (mHealth) interventions have emerged as promising solutions to bridge such gaps. Nigeria hosts one of the largest mobile phone markets in Africa, with over 200 million active subscriptions (Nigerian Communications Commission [NCC], n.d.). Short message service (SMS) remains a widely accessible communication channel, even in rural areas with limited internet connectivity. Evidence from systematic reviews confirms that SMS-based interventions can effectively improve health behaviours, such as medication adherence, smoking cessation, and disease management. Particularly when messages are concise, repeated, and culturally tailored (Hall *et al.*, 2015). In the context of food safety, initiatives such as GAIN's EatSafe program in Nigeria demonstrate that behaviour-change communications focused to informal food vendors can enhance knowledge and influence hygienic practices (GAIN, 2023).

An often-overlooked dimension of food safety in Nigeria is energy access. In rural communities such as Ibarapa Central Local Government Area, unreliable electricity supply limits vendors' ability to refrigerate perishable foods, leading to rapid spoilage and potential foodborne risks. National assessments confirm that inadequate cold-chain infrastructure contributes significantly to food losses, particularly for perishable foods such as meat, fish, dairy, and vegetables (Efficiency for Access, 2023). Recent studies indicate that solar-powered cold storage can extend shelf life, reduce spoilage, and improve vendor income (Takeshima *et al.*, 2023). Therefore, interventions that address both behavioural change (via mobile education) and structural barriers (via renewable energy access) may offer sustainable pathways to safer and more resilient informal food systems.

This study thus evaluates the effectiveness of a 12-week SMS intervention in improving food hygiene knowledge, practices, attitudes, and observed behaviors among street food vendors in

Ibarapa Local Government Area, Oyo State, Nigeria. It further examines the intersection between food hygiene and energy access by documenting spoilage losses and vendors' willingness to adopt renewable energy-based cold storage. By integrating digital health education with structural considerations, the study aims to generate evidence for scalable, cost-effective strategies to enhance food safety, strengthen vendor livelihoods, and promote public health in rural Nigeria.

## **2. METHODOLOGY**

This study adopted a quasi-experimental pre-post design without randomization to assess how mobile-based hygiene education influenced food safety knowledge, practices, and attitudes among street food vendors in Ibarapa Central Local Government Area, Oyo State, Nigeria. Random selection was not feasible because vendors in this informal sector are highly mobile and depend on daily sales for livelihood. Ibarapa Central Local Government Area is a semi-rural community with limited infrastructure, irregular electricity supply, and prolonged power outages lasting several weeks, which constrain safe food storage and refrigeration (Efficiency for Access, 2023; Takeshima et al., 2023).

The study population included both registered and unregistered street food vendors who had operated for at least six months and voluntarily agreed to participate. A total of 200 vendors were recruited based on Cochran's formula, assuming a 50% prevalence of adequate hygiene knowledge, a 95% confidence level, and a 7% margin of error. A multi-stage sampling approach was used to ensure representativeness. Major vending sites, including markets, roadside stalls, and school canteens were identified in collaboration with Environmental Health Officers (EHOs) and local vendor associations. Within each cluster, vendors were systematically selected until the desired sample size was reached, ensuring inclusion from both busy and low-traffic locations.

The intervention consisted of a 12-week short message service (SMS) hygiene education program delivered twice weekly in English and Yoruba. Each message focused on one of six core food safety themes: handwashing with soap and water, separation of raw and cooked foods, safe food storage and covering, use of clean utensils and protective clothing, proper waste disposal, and the risks of unrefrigerated food storage. Message content was adapted from the World Health Organization's Five Keys to Safer Food (WHO, 2015) and the GAIN EatSafe initiative (GAIN, 2023). Prior to intervention, messages were pretested among 20 vendors to ensure simplicity, cultural relevance, and clarity.

Data collection was carried out before and after the intervention using a structured questionnaire and an observation checklist. The questionnaire gathered information on socio-demographic characteristics, hygiene knowledge, attitudes, and self-reported practices. Observations focused on actual behaviours such as handwashing frequency, food covering, utensil cleanliness, and waste disposal practices, following validated procedures from earlier Nigerian studies (Omemu and Aderoju, 2008; Madaki and Bavorova, 2019). The key outcome variables included hygiene knowledge, attitudes, self-reported and observed practices, and energy-related indicators such as spoilage losses and willingness to adopt solar refrigeration. Data analysis was performed using IBM SPSS version 25. Descriptive statistics (means, frequencies, and percentages) were used to summarize the data. McNemar's test assessed changes in categorical variables, while the Wilcoxon signed-rank test analyzed shifts in ordinal or continuous outcomes. Logistic regression identified predictors of improved hygiene knowledge and practices, adjusting for age, education, and vending experience. This multi-method analytical approach provided a well-rounded understanding of how behavioural and

structural factors interact to influence hygiene outcomes, aligning with established evidence in food safety intervention studies (Hall et al., 2015; Singh et al., 2016).

### 3. RESULTS AND DISCUSSION

#### 3.1. Socioeconomic characteristics of the respondents

**Table 1.** Socioeconomic characteristics of the respondents

Variable	Category	Frequency (n)	Percentage (%)
Sex	Female	177	88.5
	Male	23	11.5
Age group (years)	20–30	54	27.0
	31–40	96	48.0
	41–50	32	16.0
	>50	18	9.0
Education level	None	174	87.0
	Primary	18	9.0
	Secondary	6	3.0
	Tertiary	2	1.0
Years of vending	≤ 5 years	87	43.5
	> 5 years	113	56.5

The demographic profile of the respondents in Table 1, provides crucial context for understanding the socio-economic realities shaping street food vending in Ibarapa Central Local Government Area, Oyo State. The results reveal that majority of the vendors (88.5%) were female, while only 11.5% were male. This gender dominance reflects the feminization of the informal food sector in Nigeria and other developing countries, where food vending is often an accessible livelihood for women with limited access to formal employment (Osei Mensah et al., 2020; Muinde and Kuria, 2005). Similar gender trends have been documented in urban centers such as Lagos, Accra, and Nairobi, where women constitute between 70% and 90% of street food handlers (Alimi, 2016; Donkor et al., 2022). The prevalence of female vendors aligns with broader gender and poverty dynamics in rural Africa, where women rely heavily on small-scale food trade to sustain household income and food security (FAO, 2021).

The age distribution shows that 48% of vendors were between 31 and 40 years, while 27% were aged 20–30 years, indicating that most participants are in their economically productive years. This suggests that street food vending provides vital income opportunities for adults supporting families, consistent with findings by Muinde and Kuria (2005) in Kenya and Omemu and Aderoju (2008) in Nigeria. The active participation of younger adults in this sector also highlights its resilience as a self-employment mechanism amid limited formal job opportunities, especially in semi-rural areas affected by infrastructural challenges.

Educational attainment among the vendors was notably low, with 87% reporting no formal education and only 1% possessing tertiary qualifications. This reflects structural educational disparities prevalent in rural Nigeria, particularly among women engaged in informal occupations (National Bureau of Statistics [NBS], 2022). The low literacy level is significant because it constrains vendors' ability to access and comprehend conventional training materials on food safety, which are often written in English and presented in technical terms (Nkosi and Tabit, 2021). Consequently, this limitation underscores the importance of mobile-based

educational interventions delivered in local languages, as they bypass literacy barriers and improve knowledge retention (Mensah et al., 2023).

Experience in food vending was another key feature of the respondents. Over 56.5% had been vending for more than five years, suggesting that street food vending is not merely a temporary survival strategy but a long-term occupation embedded in local economic systems. This finding aligns with similar results reported in Ghana and Tanzania, where vendors with longer experience tend to develop better adaptive skills but not necessarily improved food hygiene behaviors unless trained (Wambugu et al., 2022; Ababio and Lovatt, 2015).

The demographic structure of the respondents reflects a female-dominated, low-literacy, and economically active workforce. These characteristics highlight the need for context-sensitive, language-adapted, and low-cost interventions such as mobile phone-based learning, which can effectively reach and engage this population.

### 3.2. Knowledge of Food Hygiene

**Table 2.** Knowledge Scores (Pre vs. Post)

Indicator	Baseline (%)	Post-intervention (%)	Test Used	Statistic (df)	p-value
Knows poor hygiene causes sickness	32.0	72.0	McNemar	$\chi^2 = 28.6$ (1)	<0.001
Knows dirty hands contaminate food	38.0	74.0	McNemar	$\chi^2 = 23.4$ (1)	<0.001
Knows raw/cooked foods must be separated	13.0	49.0	McNemar	$\chi^2 = 34.9$ (1)	<0.001
Aware of symptoms of foodborne disease	17.0	68.0	McNemar	$\chi^2 = 30.2$ (1)	<0.001
Overall knowledge score (mean %)	33.0	66.0	Paired t-test	$t = 12.41$	<0.001

The findings from Table 2 show a remarkable improvement in food hygiene knowledge following the 12-week mobile-based intervention. Before the intervention, baseline knowledge among street food vendors in the study area was generally low. Only 32.0% of respondents knew that poor hygiene could cause illness, and 38.0% recognized that dirty hands can contaminate food. Awareness of the need to separate raw and cooked foods was particularly weak (13.0%), while just 17.0% could identify symptoms or transmission routes of foodborne diseases. These results are similar to the long-standing knowledge gaps documented in similar studies across Nigeria and sub-Saharan Africa, where informal food vendors often operate without formal training or regulatory oversight (Omemu and Aderoju, 2008; Nkosi and Tabit, 2021).

However, after exposure to targeted mobile phone messages, knowledge levels increased substantially. Awareness that poor hygiene can cause sickness rose from 32.0% to 72.0% ( $\chi^2 = 28.6$ ,  $p < 0.001$ ), and understanding of hand contamination improved from 38.0% to 74.0% ( $\chi^2 = 23.4$ ,  $p < 0.001$ ). Similarly, knowledge of food separation practices increased from 13.0% to 49.0%, while awareness of foodborne disease symptoms rose from 17.0% to 68.0% (all  $p < 0.001$ ). The overall mean knowledge score also increased significantly from 33.0% to 66.0% ( $t = 12.41$ ,  $p < 0.001$ ), demonstrating a strong effect of the mobile learning intervention.

These improvements are consistent with findings from Kenya and Ghana, where mobile-based educational programs successfully improved hygiene literacy among informal food handlers (Wambugu et al., 2022; Donkor et al. 2022; Mensah et al., 2023). The effectiveness of this intervention can be explained using behavioral learning principles. According to the Health Belief Model (HBM), individuals are more likely to change behavior when they perceive susceptibility to illness and understand preventive measures (Glanz et al., 2015). The repetitive and language-tailored SMS messages appear to have reinforced these cognitive shifts by improving both perceived risk and self-efficacy in safe food handling.

The post-intervention results also emphasize the potential of mobile health (mHealth) technologies in overcoming barriers linked to literacy and training accessibility. In areas like Ibarapa Central Local Government Area, where conventional workshops are costly and electricity shortages limit access to digital training. SMS-based education offers a scalable, energy-efficient solution for rural learning (Hall et al., 2015; Osei Mensah et al., 2020). The strong statistical significance ( $p < 0.001$  across all indicators) confirms that structured, context-sensitive messaging can bridge knowledge gaps that have persisted for decades in informal food systems.

### 3.3. Food Hygiene Practices

**Table 3.** Food Hygiene Practices (Pre vs. Post)

Practice	Baseline (%)	Postintervention (%)	Test Used	Statistic (df)	p-value
Handwashing before/after cooking	92.5	98.0	McNemar	$\chi^2 = 6.21$ (1)	0.013
Separation of raw/cooked foods	56.5	77.0	McNemar	$\chi^2 = 18.6$ (1)	<0.001
Different cutting boards/utensils	22.5	64.0	McNemar	$\chi^2 = 34.9$ (1)	<0.001
Covering food on display	35.0	79.0	McNemar	$\chi^2 = 42.7$ (1)	<0.001
Discarding spoiled food regularly	64.0	91.0	McNemar	$\chi^2 = 14.2$ (1)	<0.001

The analysis of Table 3 shows that food hygiene practices among street food vendors in Ibarapa Central Local Government Area improved substantially following the mobile phone-based intervention. Before the intervention, most vendors displayed inconsistent adherence to safe food handling protocols. Although 92.5% of vendors reported washing their hands before or after cooking, only 56.5% consistently separated raw and cooked foods, and 22.5% used separate cutting boards or utensils for different types of food. Likewise, only 35.0% covered food while on display, and 64.0% regularly discarded spoiled food. These baseline figures indicate partial compliance with basic hygiene standards and are consistent with earlier findings in Nigeria and other developing countries, where informal food vendors often exhibit limited food safety practices despite awareness of hygiene principles (Omemu and Aderoju, 2008; Alimi, 2016).

Following the intervention, significant improvements were observed across all indicators. The proportion of vendors washing hands increased to 98.0% ( $\chi^2 = 6.21$ ,  $p = 0.013$ ), while those separating raw and cooked foods rose from 56.5% to 77.0% ( $\chi^2 = 18.6$ ,  $p < 0.001$ ). Vendors using different cutting boards and utensils increased from 22.5% to 64.0% ( $\chi^2 = 34.9$ ,  $p < 0.001$ )

and covering of food during display improved from 35.0% to 79.0% ( $\chi^2 = 42.7, p < 0.001$ ). Similarly, the proportion regularly discarding spoiled food increased from 64.0% to 91.0% ( $\chi^2 = 14.2, p < 0.001$ ). These results indicate that the mobile-based education effectively translated knowledge gains into practical behavioral changes.

Comparable patterns have been documented in several recent studies. In Kenya, Wambugu et al. (2022) reported similar post-intervention increases in handwashing, food separation, and utensil hygiene among market vendors after receiving mobile text-based training. Donkor et al. (2022) in Ghana also found that SMS-based food safety education improved self-reported hygiene practices by over 30%. The positive behavioral changes in the present study align with these findings and demonstrate that continuous, culturally contextual reminders through mobile phones can foster habitual hygiene compliance, even among low-literacy populations. The observed improvements may be explained by the Theory of Planned Behavior (TPB), which posits that behavioral change is driven by intention, shaped by attitudes, subjective norms, and perceived behavioral control (Bosnjak et al., 2020).

### 3.4. Attitude Toward Food Hygiene

**Table 4.** Attitude Toward Food Hygiene (Pre vs. Post-Intervention)

Attitude Indicator	Baseline (%)	Post-intervention (%)	Test Used	Statistic (df)	p-value
Believes hand washing is essential before food preparation	95.0	99.0	McNemar	$\chi^2 = 4.86$ (1)	0.027
Believes food handlers should always wear aprons/hair coverings	58.0	82.0	McNemar	$\chi^2 = 22.11$ (1)	<0.001
Believes traditional cooking methods alone ensure safety	42.0	23.0	McNemar	$\chi^2 = 18.73$ (1)	<0.001
Supports continuous food hygiene education for vendors	82.5	94.0	McNemar	$\chi^2 = 10.24$ (1)	0.001
Agrees that safe practices improve business reputation and customer trust	61.0	88.0	McNemar	$\chi^2 = 28.92$ (1)	<0.001
Overall positive attitude score (mean %)	<b>67.7</b>	<b>89.2</b>	Paired t-test	t = 11.36	<b>&lt;0.001</b>

The results presented in Table 4 indicate a significant improvement in the attitudes of street food vendors toward food hygiene following the mobile-based educational intervention. At baseline, while most respondents (95.0%) already believed that handwashing was essential before food preparation, attitudes toward other hygiene-related practices were less favourable. Only 58.0% believed food handlers should always wear aprons or hair coverings, and 42.0% felt that traditional cooking methods alone ensured safety, revealing a reliance on cultural norms rather than evidence-based practices. Furthermore, 82.5% supported continuous hygiene education, and 61.0% agreed that safe practices could enhance business credibility and customer trust.

Post-intervention results showed substantial positive shifts across nearly all indicators. The proportion of vendors recognizing the importance of protective clothing increased from 58.0% to 82.0% ( $\chi^2 = 22.11$ ,  $p < 0.001$ ), while those believing traditional cooking methods were inherently safe dropped significantly from 42.0% to 23.0% ( $\chi^2 = 18.73$ ,  $p < 0.001$ ), indicating greater awareness of contamination risks. Similarly, support for continuous hygiene education rose from 82.5% to 94.0% ( $\chi^2 = 10.24$ ,  $p = 0.001$ ), and agreement that safe food practices improve customer trust increased from 61.0% to 88.0% ( $\chi^2 = 28.92$ ,  $p < 0.001$ ). The mean overall positive attitude score improved markedly from 67.7% to 89.2% ( $t = 11.36$ ,  $p < 0.001$ ), confirming statistically significant attitude change.

These results align with behavioural change theory, particularly the Health Belief Model (HBM) and the Theory of Planned Behavior (TPB), which both posit that behavioral adoption is influenced by perceived benefits, social norms, and self-efficacy (Glanz et al., 2015; Bosnjak et al., 2020). The mobile text messages appeared to enhance vendors' perception of personal responsibility for food safety and their belief that hygienic practices yield tangible business and health benefits. As attitudes became more favourable, vendors demonstrated greater motivation to apply what they learned in daily operations.

Comparable findings have been reported across sub-Saharan Africa, where targeted communication interventions have shifted food handler attitudes toward safer practices. Wambugu et al. (2022) observed that mobile learning interventions in Kenya not only improved hygiene knowledge but also strengthened vendors' belief in the importance of consistent cleanliness and protective clothing. Similarly, Nkosi and Tabit (2021) in South Africa found that continuous exposure to hygiene information was a strong predictor of positive attitudes among street food vendors. In Ghana, Mensah et al. (2023) reported that participants in mobile learning programs demonstrated increased openness to adopting new hygiene norms, emphasizing the role of accessible technology in influencing mindset transformation.

The reduction in vendors' reliance on "traditional safety beliefs" is particularly significant for Ibarapa Central Local Government Area, where cultural food-handling practices often override formal safety guidelines. The mobile messages challenged these misconceptions by framing hygiene as both a health imperative and an economic advantage, reinforcing the idea that clean, safe food enhances reputation and customer retention (Donkor et al., 2022).

### 3.5. Energy Access and Spoilage Losses

**Table 5.** Energy Access and Spoilage Losses

Indicator	Baseline	Post-intervention	Test Used	Statistic (df)	<i>p</i> -value
Vendors with refrigeration (%)	5.0	12.0	McNemar	$\chi^2 = 8.12$ (1)	0.004
Reliable grid supply (hours/day, mean)	0.2	0.3	Wilcoxon signed-rank	$Z = -1.12$	0.261
Weekly spoilage loss (₦, mean)	₦4,200	₦2,300	Wilcoxon signed-rank	$Z = -6.78$	<0.001
Willing to adopt solar refrigeration (%)	54.0	81.0	McNemar	$\chi^2 = 25.3$ (1)	<0.001

The results presented in Table 5 highlight the dual challenge of limited energy access and high postharvest food losses among street food vendors in Ibarapa Central Local Government Area,

and the modest improvements recorded following the mobile phone-based educational intervention. At baseline, only 5.0% of vendors reported access to functional refrigeration, reflecting widespread energy deprivation in the study area. This aligns with existing national statistics showing that fewer than 15% of rural Nigerian households have stable electricity access for food preservation (International Energy Agency [IEA], 2023).

Post-intervention, the proportion of vendors with refrigeration rose to 12.0% ( $\chi^2 = 8.12$ ,  $p = 0.004$ ). While this increase appears modest, it signifies a growing awareness and willingness among vendors to invest in or share small-scale refrigeration facilities, including solar-powered units, as part of improved food safety practices. However, grid reliability remained critically low, with mean daily electricity supply improving only marginally from 0.2 to 0.3 hours per day ( $Z = -1.12$ ,  $p = 0.261$ ). This finding underscores the persistent infrastructural constraint that limits cold-chain maintenance in many rural communities, a situation consistent with reports by Takeshima et al. (2023), who noted that unreliable grid power remains a key driver of postharvest losses in Nigeria's informal food sector.

A notable outcome was the significant reduction in weekly spoilage losses, which declined from an average of ₦4,200 to ₦2,300 ( $Z = -6.78$ ,  $p < 0.001$ ). This 45% reduction can be attributed to improved handling and storage behaviors promoted by the mobile intervention, including covering food, discarding spoiled items promptly, and minimizing exposure to heat and pests. Such behavioural adjustments, even in the absence of stable power, can substantially extend food shelf life, as observed in similar interventions across Ghana and Tanzania (Afoakwa et al., 2022; Mwakatobe et al., 2020).

Similarly significant was the increase in vendors' willingness to adopt solar refrigeration, rising from 54.0% at baseline to 81.0% post-intervention ( $\chi^2 = 25.3$ ,  $p < 0.001$ ). This shift suggests a growing recognition of the role of renewable energy solutions in sustaining food hygiene and reducing economic losses. The findings are consistent with studies by Efficiency for Access (2023) and Green et al. (2021), which demonstrated that solar-powered cooling systems can reduce food spoilage, lower energy costs, and enhance livelihoods for small-scale vendors and farmers in off-grid regions.

The modest yet meaningful improvements observed here reflect an important behavioural spillover effect: exposure to mobile-based hygiene education appears to have stimulated energy consciousness and technological openness among vendors. By understanding the relationship between temperature control and microbial safety, vendors became more receptive to alternative energy technologies such as solar cooling. This behavioural linkage between food hygiene and energy use is a relatively underexplored but crucial dimension of sustainable food systems (FAO, 2022).

### **3.6. Observed Hygiene Practices**

Table 6 presents the changes in observed hygiene practices before and after the mobile phone-based intervention. These observations provide an objective measure of vendors' behavioural transformation beyond self-reported data. At baseline, hygiene conditions at most vending sites were visibly poor. Only 26.0% of vendors had soap available for handwashing, 35.0% covered food on display, and 22.0% used separate containers for raw and cooked items. In contrast, 68.0% of stalls exhibited visible dust or pest exposure, and only 18.0% maintained proper waste disposal systems. These figures are consistent with findings from earlier studies in Nigeria, Ghana, and Kenya, where poor environmental sanitation and limited access to hygiene

infrastructure were identified as key barriers to safe street food practices (Omemu and Aderoju, 2008; Ababio and Lovatt, 2015; Alimi, 2016).

**Table 6.** Observed Hygiene Practices

Observed Indicator	Baseline (%)	Post intervention (%)	Test Used	Statistic (df)	p-value
Soap available at stall	26.0	74.0	McNemar	$\chi^2 = 38.6$ (1)	<0.001
Food covered on display	35.0	79.0	McNemar	$\chi^2 = 42.7$ (1)	<0.001
Separate containers for raw/cooked food	22.0	62.0	McNemar	$\chi^2 = 29.3$ (1)	<0.001
Visible pests/dust near food (negative)	68.0	29.0	McNemar	$\chi^2 = 33.5$ (1)	<0.001
Proper waste disposal at site	18.0	54.0	McNemar	$\chi^2 = 27.2$ (1)	<0.001

Following the 12-week SMS-based intervention, all observed indicators improved significantly ( $p < 0.001$ ). The availability of soap at stalls rose from 26.0% to 74.0% ( $\chi^2 = 38.6$ ,  $p < 0.001$ ), indicating greater prioritization of hand hygiene. Similarly, food covering practices increased from 35.0% to 79.0%, and the use of separate containers for raw and cooked food improved from 22.0% to 62.0% ( $\chi^2 = 29.3$ ,  $p < 0.001$ ). Negative hygiene indicators also declined sharply; stalls with visible dust or pest presence decreased from 68.0% to 29.0% ( $\chi^2 = 33.5$ ,  $p < 0.001$ ). Additionally, proper waste disposal improved from 18.0% to 54.0% ( $\chi^2 = 27.2$ ,  $p < 0.001$ ).

These results confirm that mobile messaging not only enhanced knowledge and attitudes but also translated into observable behavioral improvements. Similar outcomes have been documented by Wambugu et al. (2022) in Kenya, where visual cleanliness and waste management improved following mobile-based hygiene interventions. Donkor *et al.* (2022) also reported that vendors who received regular text reminders demonstrated higher compliance with hygiene standards during on-site inspections compared to control groups.

The observed behavioural changes can be interpreted through Bandura's Social Cognitive Theory, which emphasizes learning through observation, reinforcement, and self-efficacy (Bandura, 2004). The repetitive SMS messages may have reinforced hygiene norms while fostering self-confidence in maintaining cleanliness even under resource constraints. Vendors who internalized these messages likely influenced their peers, leading to collective behavioural shifts across vending clusters.

Importantly, these improvements occurred despite persistent infrastructural limitations such as irregular electricity and limited access to clean water. This underscores the practicality of low-cost, communication-based interventions in contexts where traditional training workshops or monitoring are infeasible. The observed increase in food covering, use of soap, and waste management indicates that behavioural reinforcement via mobile messaging can lead to measurable environmental and public health benefits, even without large infrastructural investments.

Moreover, the findings suggest a synergistic effect between improved hygiene and energy management practices discussed earlier.

### **3.7. Correlation Between Knowledge, Practices, and Attitude**

The results across Tables 2 to 4 suggest a strong, positive relationship between food hygiene knowledge, attitudes, and practices among street food vendors in Ibarapa Central Local Government Area. Improvements in one variable appeared to reinforce gains in the others, indicating that the mobile-based educational intervention effectively strengthened cognitive, affective, and behavioural dimensions of hygiene behaviour. Statistical analyses revealed significant pairwise correlations ( $p < 0.01$ ) between knowledge scores and both self-reported and observed hygiene practices, as well as between attitudes and actual behavior.

This interrelationship aligns with long-established behavioral change frameworks such as the Knowledge–Attitude–Practice (KAP) model, which posits that knowledge acquisition precedes positive attitudinal shifts, ultimately leading to behavioural change (Launiala, 2009). In this study, vendors who demonstrated higher post-intervention knowledge scores were also more likely to report frequent handwashing, food covering, and separation of raw and cooked foods. Similarly, those who held stronger beliefs about the importance of hygiene tended to comply more consistently with recommended practices.

Comparable findings have been reported in similar low-resource contexts. Nkosi and Tabit (2021) observed a positive correlation between food safety knowledge and hygienic behaviour among South African street food vendors, noting that knowledge alone was insufficient unless accompanied by attitudinal change. In Ghana, Mensah et al. (2023) found that mobile learning interventions enhanced both knowledge and attitudes, leading to improved compliance with food hygiene standards. Likewise, Donkor et al. (2022) documented that sustained behavioural improvements were more likely among vendors who demonstrated both cognitive understanding and motivation to act.

The strong correlation between attitude and practice in this study also underscores the mediating role of perceived behavioral control, a key construct in the Theory of Planned Behavior (TPB) (Bosnjak et al., 2020). Vendors who felt capable of maintaining hygiene—despite infrastructural limitations such as irregular power supply or lack of water, were more consistent in applying safe practices. The motivational effect of mobile text messages, framed in simple language and aligned with local realities, likely increased self-efficacy and reduced the perceived difficulty of maintaining good hygiene.

Furthermore, the interplay between hygiene knowledge and energy practices observed in Tables 5 and 6 reflects a behavioural spillover effect, where improved awareness in one area (food safety) influenced positive behaviours in another (energy use). Vendors who understood that temperature control reduces microbial contamination were also more inclined to explore solar-powered refrigeration solutions. This cross-domain relationship supports recent findings that integrated behavior change communication, combining health, energy, and livelihood messaging, can yield broader developmental outcomes in resource-limited settings (FAO, 2022; Green et al., 2021).

## **4. CONCLUSION**

The study demonstrated that mobile phone–based hygiene education can significantly improve food hygiene knowledge, attitudes, and practices among street food vendors in rural Nigeria. Post-intervention results showed marked increases in awareness of foodborne risks, adoption of safer handling practices, and more positive hygiene attitudes. Observable improvements such as increased handwashing, cleaner display conditions, and proper waste management

confirm that behavior change is achievable through simple, culturally tailored SMS interventions.

Beyond hygiene, the intervention also contributed to energy resilience, with reduced spoilage losses and greater willingness to adopt solar-powered refrigeration despite limited grid supply. These outcomes highlight the dual potential of mobile technology as a low-cost tool for public health education and sustainable energy transition in informal food systems. Strengthening such digital and renewable initiatives can enhance food safety, reduce economic losses, and promote healthier livelihoods in energy-poor rural communities.

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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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## DEVELOPING A SMART CAMPUS SAFETY AND SECURITY FRAMEWORK USING INTERNET OF THINGS (IOT): A CASE STUDY

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### Abstract

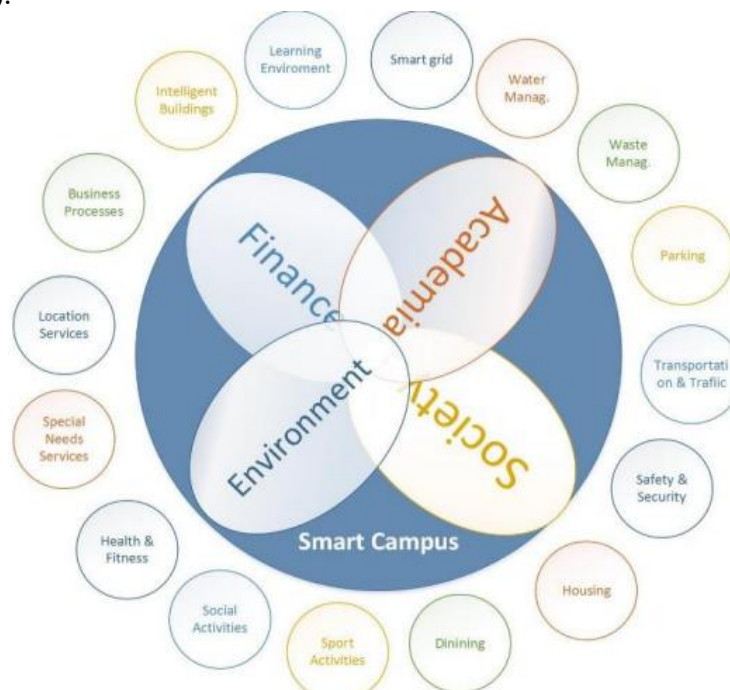
*Tertiary institutions around the world have embraced the development of smart campuses as a means of monitoring students' activities on campus in recent years. Smart campus, adaptation of smart city, use of campus environment as the foundation for project development. Smart learning, smart libraries and smart sports complexes are examples of smart campus applications, smart healthcare, smart water and waste management, smart energy consumption, smart security and safety management and so on. These procedures make it easier to work together on campuses. This paper focuses on smart campus design on security and safety framework with an emphasis on intrusion on critical facilities that require access permission. When an intruder is detected, the application uses embedded system cameras, which are cameras designed for microcontrollers to receive notification with a new photo and/or sensor data. Intruders are detected using passive infrared (PIR) motion sensors, and the information is sent to the premise owner via telegram bot (Telegram App). The owners can also request general conditions of things from a remote location, whether within the premises or outside the continent, through bi-directional communication. The technology was validated in real-world scenarios and the feedback data was analyzed for potential intruder. The results showed that the model have the capacity of detecting intruder into the defined area and relate information and location of the intruder to the owner of the premises in real-time anywhere in the continent for prompt action. Conclusively, the developed smart campus safety and security framework using IoT has improved the campus security and safety system.*

### 1. INTRODUCTION

The majority of Nigeria's higher institutions are currently dealing with security and safety issues. Recent increase in kidnapping in Nigerian institutions has become worrisome and the safety on the Nigerian institution campuses became a growing concern to stakeholders among the campus community and the across the country. A serious security breach occurred sometime ago at the National Institute of Construction Technology and Management's campus, putting lives and the institution's properties in danger. This was made easy due to the school's campus's location on the outskirts of the city. To protect lives and property, the school has hired

private security guards. However, due to the high cost of maintaining this approach, it has recently been discovered that it is no longer sustainable. Hence, new ways that is sustainable to secure lives and properties in the Institute is highly required. As a result of the useful information learned about creating smart cities, many researchers have recently focused on the concept of a smart campus. A tertiary institution campus is essentially a mini-city that provides a variety of services to a wide range of customers. The Smart Campus research area at Urban, Internet of Things (IoT) is critical. As a result, the application of IoT on smart campuses provides useful insight into the application of urban IoT (Alghamdi and Shetty, 2016). The idea is to create a campus that makes the best use of its resources, provides high-quality services to the campus community, and has significantly lower operating costs.

The Internet of Things (IoT) is now an unavoidable component of the smart campus in the industrialized world. IoT is a communication medium that have gained capacity overtime for varieties of objects to the internet. The ability of the Internet of Things to connect a variety of everyday devices to the internet is what ensures its survival as a communication paradigm. The objects are but limited to: Sensors, robotics, security locks, alarms, drones, appliances, smart grid systems, office supplies, and other items are examples, but they are not limited to them. Despite the fact that the Internet of Things is still in its early stages, numerous applications and standards have been developed for it in a variety of fields, including home automation, smart grids, water and waste management, traffic control, autonomous vehicles, healthcare assistance, industrial automation, and security, which is the focus of this current research work. The smartness of campus can have diverse applications depending on the services that is been conveyed and received in the campus. The campus can be divided into four (Abdullah, et al. 2019) areas: intelligent buildings, campus smart grid, learning environment and other applications. Figure 1 shows the Impacts and applications of smart campus concept (Alghamdi and Shetty, 2016).



**Figure 1.** Impacts and Applications of Smart Campus Concept

Campus security is critical; there are sensor systems or video observation frameworks that generate data about any event of the 24 hours of the day. The capability of this framework enables the use of their information for variety of tasks, such as pattern recognition or

identifying the population's unique needs (Villegas-Ch et al., 2019). The checking limit that was added to the investigation cycle enables campus administrations to self-regulate and carry out identification. Campus security is inextricably linked to human tracing data because it focuses on individual activities and social gatherings. The occurrence of social events, unusual groupings of people, individual misbehaviour, the movement of criminals and the missing, and human behaviours in disasters can all be inferred from mined data (Pan, et al., 2013). Based on the data collected about the crowd and human behaviour, campus security could be improved in a variety of ways, including: i) identifying individual misbehaviour from aberrant traces that may indicate probable individual misbehaviour; and ii) searching for and monitoring important individuals. People who went missing or were involved in a disaster could be found. Traces of alleged criminals could point to real criminals, gangs, or dangerous neighbourhoods.

This current research is an off-shoot of the comprehensive smart campus project that is currently being developed. The study proposes an IoT-based safety and security architecture that would improve safety on the NICTM campus in Uromi. This study describes the proposed "Smart Campus" concept and architecture in order to define the underlying criteria for its construction and provide a strategic framework for its components.

## **2. LITERATURE REVIEW**

Every person on the planet is still looking for safety. The greatest fear of any person is that his/her surroundings is safe and if not, it will no longer be safe for him/her and that his/her life will no longer be safe. Furthermore, the security conditions of Nigeria as a country has inevitably seep into the tertiary institutions. Campuses cannot be safe in a setting where Nigerian residents are not safe.

The majority of the students on campuses are between the ages of sixteen and thirty-five. The young are at a stage in their lives when they have an insatiable desire for adventure. As a result, people begin to engage in anti-social behaviours such as drinking, smoking, drug use and joining cults. Youth can be equally beneficial at this point in their lives if they choose to be useful to themselves. Majority of our students are so active, our schools' security needs to be tightened to limit and reduced youth exuberance. Most institutions now employ private security, which can be costly to maintain and this has increase cost of running institutions in the country. The concept of an intelligent system for campus security and safety has recently gained popularity in the industrialized world, but adoption in this country has been extremely slow. The need for a smart campus is driven by the variety of services offered to various user groups on campuses, who expect lower costs while receiving high-quality services (Alghamdi and Shetty, 2016). The effects of campus services extend beyond the academic community into the environmental, financial and social spheres. Internet of Things (IoT) will unavoidably be used on smart campuses to bring variety of services needed in the campus. A smart campus typically includes, among other things, a smart grid, water and waste management, intelligent buildings, learning environments, parking, traffic, transportation, business processes, location services, safety and security, housing and dining, social and sporting events, health and fitness programmes and services for people with special needs (Alghamdi and Shetty, 2016). Also, Abdullah et al. (2019) proposed a smart campus framework for safety and security system in the University campus using IoT technologies which was tailored to fit any University campus that would act as an instantaneous responder to incidents that may happen on campus. He summarized the challenges into technical, financial and political and their work highlight future area of improvement.

As a result of modern and evolving technologies, people's living standards and overall quality of life have improved. However, a good education is an important component in the development of society because it shapes future generations and influences their thought processes. It appears that there is a current need to incorporate new technological developments into existing educational institutions to meet required need of services. Furthermore, combining educational institutions with new technology is one solution to the on-going issue of using sustainable resources. Smart campuses, like smart cities in general, can only serve as a catalyst for changing how educational institutions are currently organized (Harrison et al., 2010). How people experience and navigate data challenges in their daily lives is becoming increasingly important as communication networks expand due to digitalization, connective devices, and the Internet of Things (IoT), with higher education serving as a significant data frontier (Van Dijck, 2014 and Beer, 2019).

Villegas et al. (2019) uses the concept of smart cities to define smart campuses as the integration of three key axes, including big data management and analysis, data centralization, and IoT-based data collection. As a result of the integration of axes, traditional campuses can effectively manage the information generated on their own.

The report by CenturyLink (2018) recommends implementing IoT in three areas to improve campus safety and security: asset protection, facility access control, and interactive signage and kiosks. The use of track-able beacons on high-value resources can help millions of organizations secure their investments. To avoid disaster, IoT provides campuses with control over their buildings, including who can enter and when, as well as a log of entry and exit. IoT can be used in an emergency to display critical information on interactive signage and kiosks. So, it's safe to say that using IoT to improve safety and security is a good idea, and it's also a critical component of creating a smart campus. This study proposes an IoT-based safety and security architecture that would improve safety on the NICTM campus in Uromi using passive infrared (PIR) motion sensors. The information collected is sent to the premise owner via Telegram bot (Telegram App) through bi-directional communication for him/her to take prompt action.

### **3. CONCEPTUAL FRAMEWORK OF THE SMART SECURITY AND SAFETY CAMPUS PROJECT**

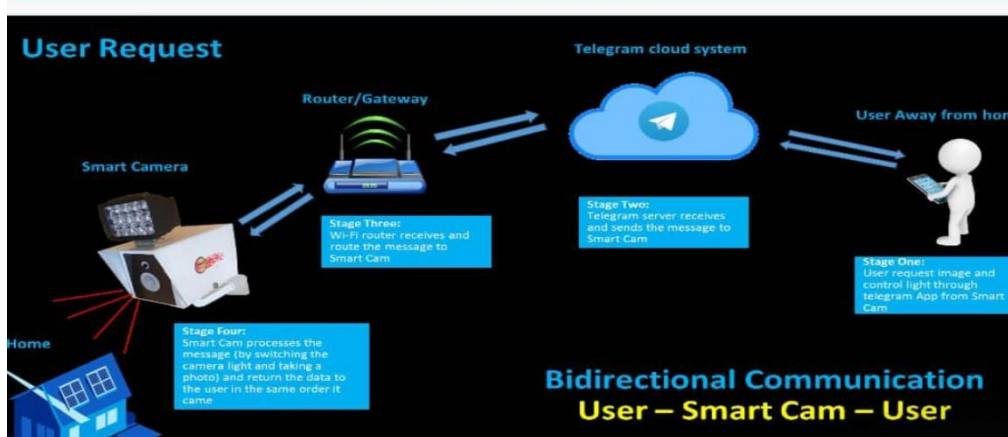
The entire project is a comprehensive smart campus proposal that covers the following as shown in the Figure 2. However, the current research focuses on the safety and security aspect of the proposed comprehensive smart campus project. The design and implementation of the security system architecture is described below.



**Figure 2.** Dashboard that integrates all the Components of the Framework

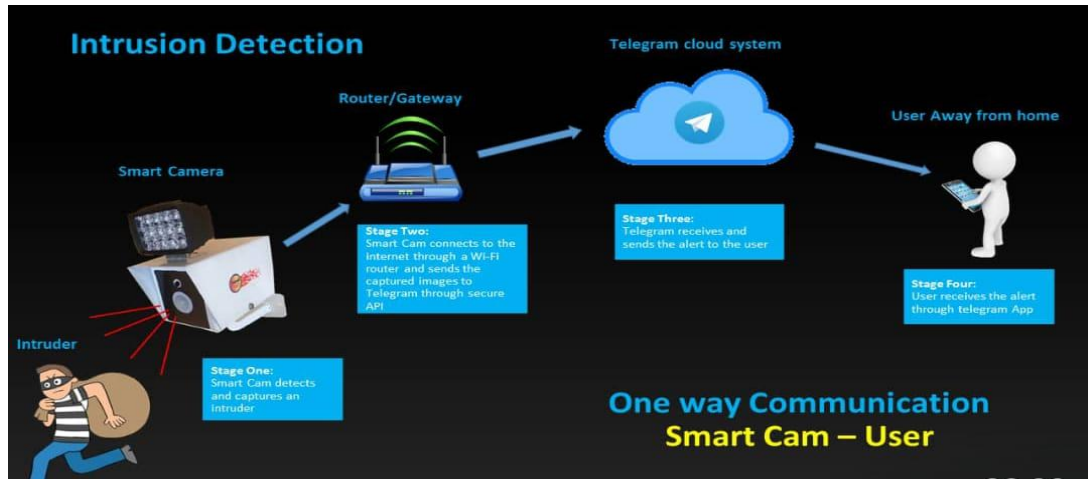
The entire architecture involves creating a Telegram bot to control the surveillance system, so that the system can monitor the premise from anywhere (as long as you have internet access on your smartphone). The system works by detecting unauthorized intruders, using proximity sensors to detect movements, and take the photo of the event and send the picture to the premise owner through the Telegram app. It was designed in such a way to ask the system to send information by command. The proposed smart security campus works based on two communication systems. These are:

1. Bi-directional communication (User-smart cam-user Interaction): The communication is imitated from the user’s interaction and it queries the setup for proceedings at the other end. If any intrusion is detected in an authorize location, it send photo signal back to the user for prompt action.



**Figure 3.** Bidirectional Communication Architecture of the Smart Security

2. One-Way communication (Smart Cam-User) communication. The communication is initiated from the user's interaction and it queries the setup for proceedings at the other end. If any intrusion is detected in an authorize location, it send photo signal back to the user for prompt action.



**Figure 3.** One-Way Communication Architecture of the Smart Security

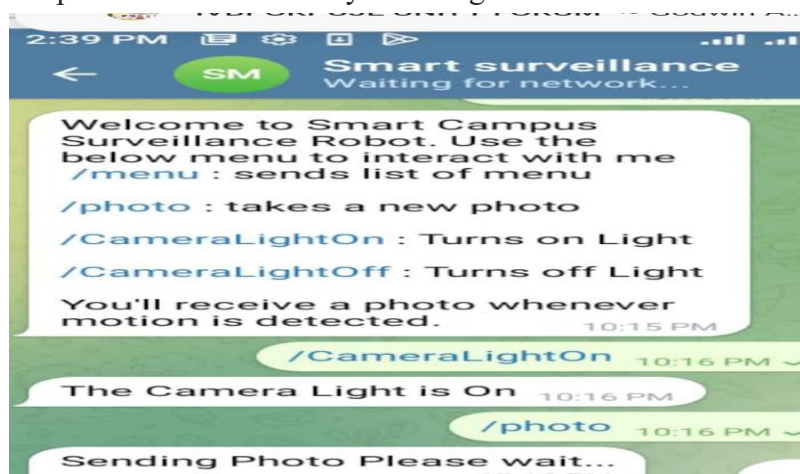
The design of the system enclosure was constructed in such a way to prevent harsh weather acting on it. A printed circuit board (PCB) was designed for the work. Readings were initiated using the requests for the latest sensor readings that were attached to the system's unit, like temperature, etc. The C++ programming language was used to implement the design of the smart campus. The system was validated in the next phase of the study.

#### 4. TESTING AND VALIDATION

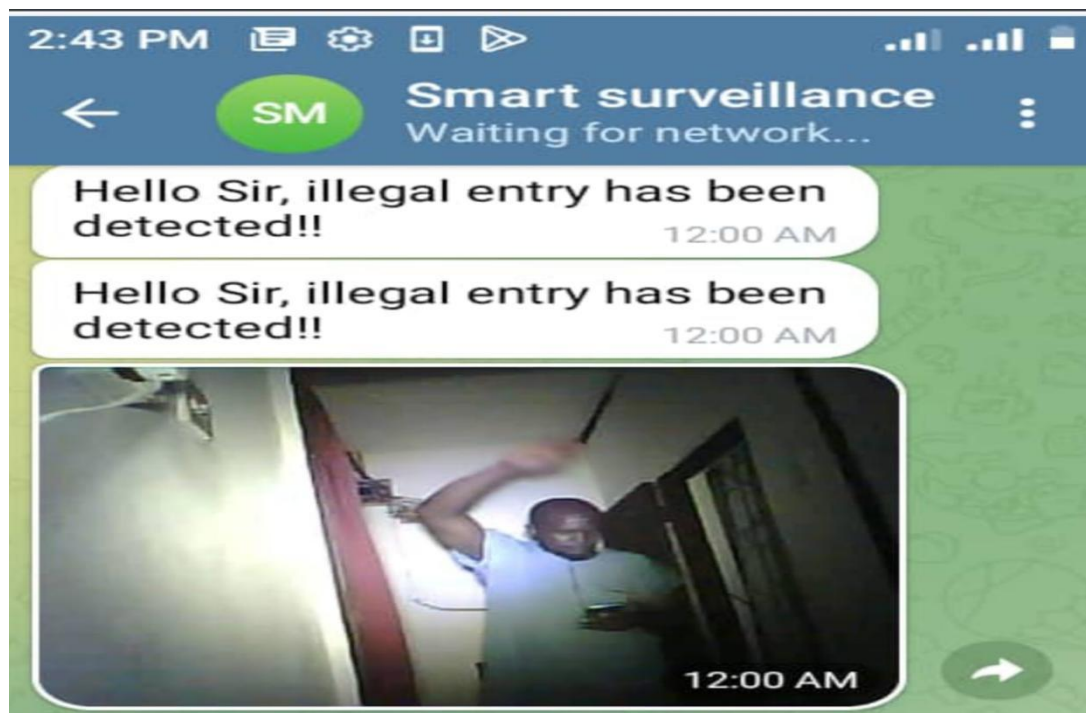
The system was validated using real life data for the evaluation. The process was initiated from the extreme ends of the school to test the efficiency of the data sent to the bot telegram system. The following commands were used to interact with the system as shown in the Figures 5 and 6 below:

Start: sends a welcome message containing the valid camera control commands.

Photo: takes a new picture and sends it to your Telegram account.



**Figure 5.** Sends a welcome message containing the valid camera control commands



**Figure 6.** Takes a new picture and sends it to your Telegram account

It was observed that once an authorized entry was detected, the information was relayed to the user almost immediately. This was the case in the six locations that were tested for the smart security and its efficiency in the day was determined. The result displayed shows a good quality display of the photos taken in real time. However, the reverse was the case when we try to initiate the unauthorized entry into the key areas of the institution at night. The result showed a poor quality feedback of the photos taken. This aspect was later corrected by introducing the light-on command when conditions are not favorable to get good quality photos in real time. Several tests were conducted and result displayed showed prompt response in terms of the light on command and the quality feedback of the photos taken in real time at the various spot was very clear due to the light on command introduced to the system.

## **5. CHALLENGES AND FUTURE WORK**

The challenges encountered in the course of the project work were poor internet connectivity across the campus premises. Furthermore, there were issues that arose from the delay in feedback photo from the point of camera to the bot telegram in a remote location as a result of poor internet connectivity.

## **6. CONCLUSION AND RECOMMENDATION**

The study developed and validated a smart security and safety framework for the NICTM's campus and its relevance was shown in the system since the campus is situated in the outskirts of the Amedokhian town with bushes on both sides of the campus. Hence, its development is a critical asset to the security outfit of the campus. Basically, it is recommended in future work that the camera should be designed in such a way that is not clearly visible to the would-be offender or intruder. It should be such a way that nobody will suspect or anticipate that there is a camera placed in that location. Finally, we intend to expand the current project by providing a big data base for video recording of the sessions and uploading the information collected to crowd directing.

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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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## THE EFFECT AND PERFORMANCE OF ELECTRON TRANSPORT MATERIAL ON C60-BASED PEROVSKITE SOLAR CELL

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### ABSTRACT

Solar Energy System explored the use of photovoltaic technology in converting solar irradiance using the required materials but effective materials are required in the conversion process at different segment of solar cells. Electron Transport Material (ETM) plays a remarkable role in the conversion of irradiance received from the sun into electricity. This work presents the behaviours of ETM such as fullmade (C60) with respect to organic Hole Transport Material (HTM) NiO and an inorganic perovskite material called potassium germanium chloride ( $K_3GeCl_3$ ) as an absorber in the solar cell. Using finite element method as contain in COMSOL Multiphysics software, Poisson and electrical transport equations were computed for an optimal solution with the highest output conversion efficiency of the solar cell, the thickness size of the electron transport layer and light absorption layer. A specific designed structure with an architectural position of FTO/C60/ $K_3GeCl_3$ /NiO/Au was used for the purpose of this investigation. This designed structure was able harness a power conversion efficiency (PCE) of 19.04% with an output open circuit voltage of 0.78V, a short circuit current of 31.02mA, and fill factor of 0.787. The results show that effective material in the ETM and HTM can be used to assist in creating an improved, efficient and good performance perovskite based solar cell.

### 1.0 INTRODUCTION

Solar Photovoltaic technology is one of the major drivers towards sustainable energy globally. Solar photovoltaic systems have since became the most widely and commonly used renewable energy technology in both rural and urban areas around the world, and this have been particularly for both commercial and residential buildings. The demand for energy around the world is directly proportional to the population increased more especially in the sub-Saharan Africa (SSA) as indicated in (IRENA and AfDB, 2022). The use of solar energy has emerged significant and most viable option for solution due to the energy needs in both commercial and residential buildings (Vural, November 2019). Abundant radiation is some part of the world have made solar energy an energy demand solution for the requirement of the various loads. But this abundant energy that is left untapped can only harness using the right technology, the right materials and optimisations tools (IRENA 2024). Perovskite solar cell is among the most

promising, emerging solar cells technologies and the fourth-generation solar cells that utilizes organic-inorganic perovskite materials (Khalid et al., 2021). These materials have shown a significant increase in efficiency, rising from 3.8% to 25.5% in just within a decade (Perovskite et al, 2022). The aim of this study is to investigate the effectiveness of ETM and optimizing the efficiency of solar cells using diverse materials while utilising potassium germanide chloride ( $K_3GeCl_3$ ) as absorber layer.

## 2.0 METHODOLOGY

In modelling 3D solar cell, three axes of the geometry must define unlike 2D where only axes are being considered. In 3D, x, y and z axes considered with relevant dimensions as indicated in table of parameters (Table 1). According to the settings in COMSOL Multiphysics software, the axes are being assigned as width, depth and height, where the height is the z-axis, width is the x-axis and depth is the y-axis. The geometrical input parameters values for the ETL/Absorber/HTL are as indicated Table 2, under global definition in the model builder. The geometry is classified or sub-divided based on type and material to be used in the numerical modelling. Geometrically, all the layers or regions contains different dimensions with their respective doping concentrations, which is determined by the type of layer or region. The doping concentration range from a minimum to maximum concentration as mentioned in (Belarbi et al, 2022). The COMSOL Multiphysics software uses the Finite Element Method (FEM) to solve continuity equations as shown in Equation (1) while simulating solar cells to find the current density distribution (Baig et al, 2014).

$$-\nabla \cdot (\sigma \nabla V - j) = Q \quad (1)$$

Where:

- V is the electric potential,
- j is the current density,
- Q is the generated current, and
- $\sigma$  is the conductivity of the material

The semiconductor module contains all the necessary partial differential equations (PDE) which govern the electronic transportation mechanism in the semiconductor material (Rupa et al, 2023). The generation rate contributes in terms of reflecting the absorption behaviours, which added to the built-in of the current densities output in form user-defined generation while the recombination techniques are being considered within the Shockley-Read-Hall (SRH) under the trap assisted recombination (Boubakri et al, 2021).

The photo-generation rate can be expressed as.

$$G(x) = \int_0^\alpha \alpha(\lambda) \phi(\lambda) \exp(-\alpha(\lambda) x) d\lambda \quad (2)$$

where x – The depth into the solar cell from the surface

$\lambda$ – The wavelength

$\alpha(\lambda)$  – The Absorption coefficient

$$\alpha(\lambda) = \frac{4\pi}{\lambda} K(\lambda) \quad (3)$$

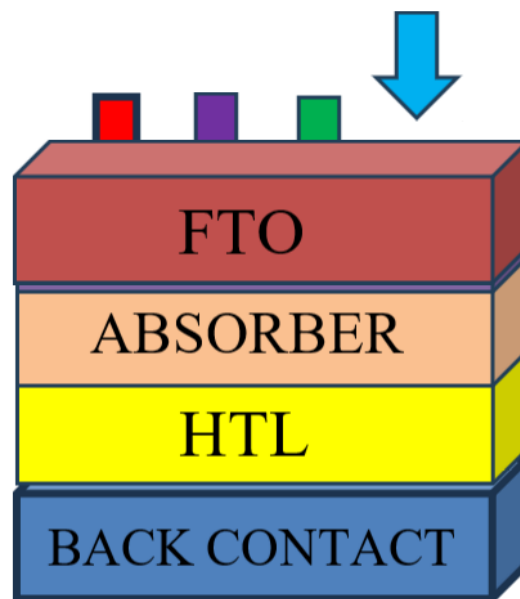
where  $K(\lambda)$  – The extinction coefficient

$\phi(\lambda)$  – The incident photons flux, as in:

$$\phi(\lambda) = \frac{\lambda}{hc} F(\lambda) \quad (4)$$

$F(\lambda)$  – The spectral irradiance, at approximated value of AM 1.5 Spectrum (Boubakri et al, 2021). Meshing also contributes significantly in determining the output of the numerical simulation, where ranges of discretisation which depend on the type of selected mesh (Zandi et al, 2020). The smaller the discretisation of the geometry the higher the degree of freedom and this degree of freedom is being generated as a result of the meshing (Parasuraman et al, 2024). The mesh ranges from extremely coarser (bigger in size) to extremely fine (smaller in size). Personal Computer (PC) or laptop need a high specification capacity to carry execute finer to extremely finer mesh due to high memory space required during the execution of the simulation (Lawal et al, 2024).

Perovskite Solar cells (PSC) is an emerging solar cell technology that has gained research attention within the last two decades with tremendous improvement in terms of power conversion efficiency (PCE) (Roose et al, 2022). Perovskite solar cells were utilized in this research to have an optimal characteristics output that can compete with the best performing solar cells that have been published. The PSC materials to be considered in this work as electron transport materials (ETM) is fullerene (C60) while NiO was considered as hole transport materials (HTM). The main absorption material based on its high absorption capacity as compared to other materials is potassium germinate chloride (KGeCl<sub>3</sub>) (Sarhani et al, 2023).



**Figure 1.** Typical Perovskite Solar Cell Structure (Lawal et al, 2024)

KGeCl<sub>3</sub> have ability to increase its charge carrier mobility and reduced recombination losses with high stability in its designed. Another absorption material used in this research is silicon material as the main substrate in the solar cells because of efficient, stability and withstand harsh environmental conditions, a metal contact is being used at both the front and the back contact as shown in Figure 1.

**Table 1.** General 3D Solar Cell Input Parameters Settings

Parameter	Expression	Value	Description
Temperature	300[K]	300 K	Input temperature
Voltage	0[V]	0 V	Biasing Voltage
Lambda0	300[nm]	3E-7m	Initial wavelength
Lambda1	1000[nm]	1E-6m	Final wavelength
Frequency	c_const/lambda0	9.9931E14 1/s	Initial Frequency
Width	0.2[um]	2E-7m	Width of the geometry
Depth	0.3[um]	3E-7m	Depth of the geometry
Height	0.93[um]	93E-7M	Height of the geometry
Irradiance	1000 (AM1.5)	1000Watt/m <sup>2</sup>	Input Irradiance

**Table 2.** Input parameters settings for ETL/Absorber/HTL

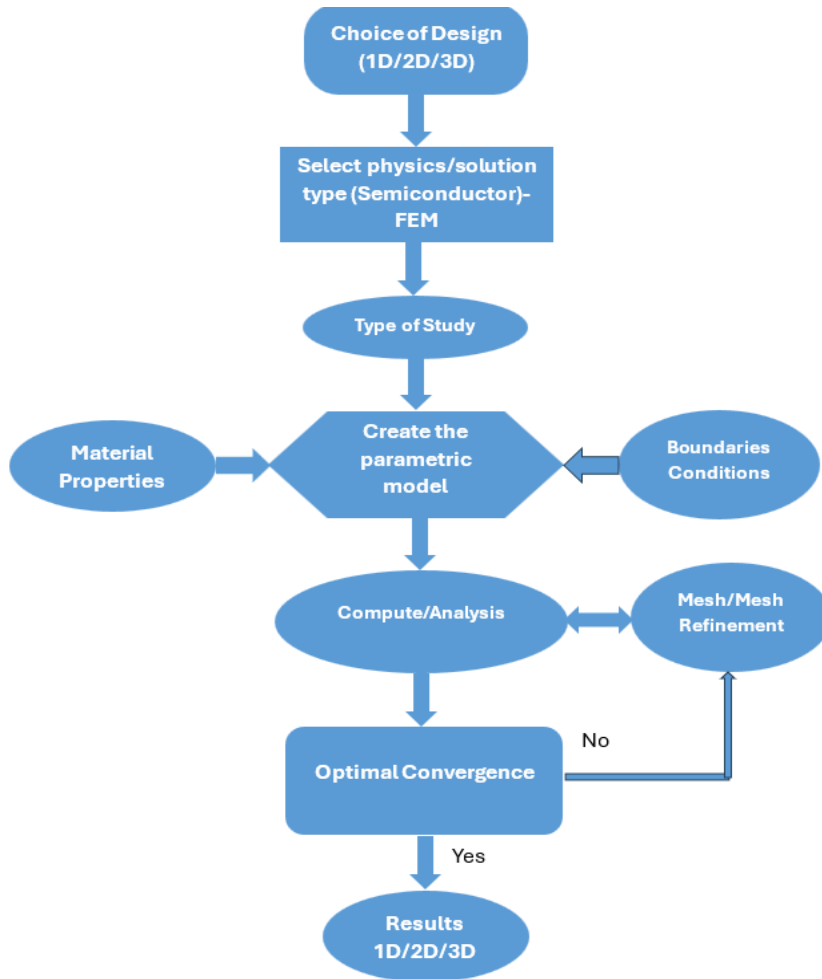
Name	NiO	C60	KGeCl3
Thickness (um)	0.2	0.1	0.3
Band gap, E <sub>g</sub> (eV)	3.2	1.7	1.49
Electron Affinity, $\chi$ (eV)	3.9	3.9	3.8
Relative permittivity, $\epsilon_r$	9	4.2	7
CB effective density of states, N <sub>c</sub> (cm <sup>-3</sup> )	1e21	8e19	3.76e19
VB effective density of states, N <sub>v</sub> (cm <sup>-3</sup> )	2e20	8e19	2.10e18
Electron mobility, $\mu_n$ (cm <sup>2</sup> /Vs)	0.02	8e-2	850
Hole mobility, $\mu_p$ (cm <sup>2</sup> /Vs)	2	3.5e-3	450
Uniform acceptor density, N <sub>a</sub> (cm <sup>-3</sup> )	0	1e17	1e15
Uniform donor density, N <sub>d</sub> (cm <sup>-3</sup> )	5.1e19	0	1e9

### 3.0 Simulation Process

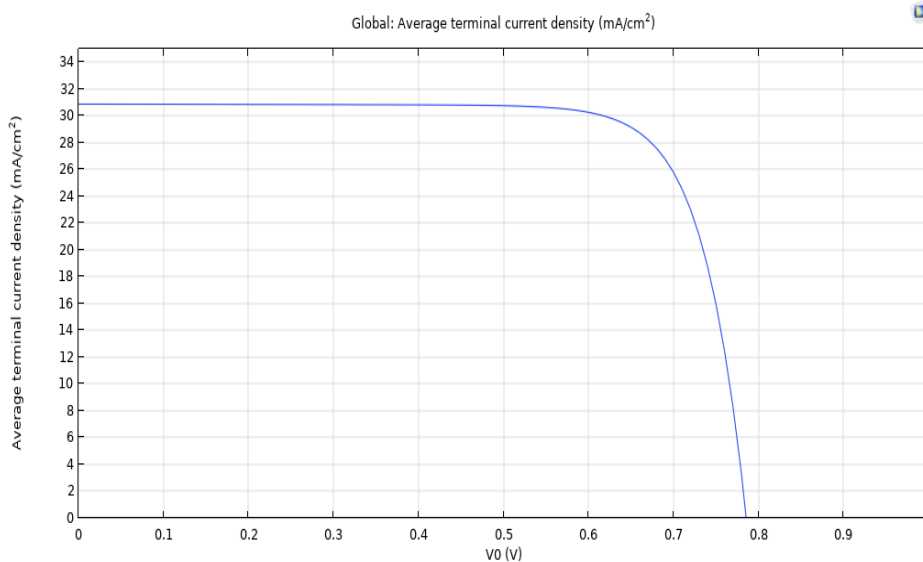
The simulation processes are based on the COMSOL Multiphysics numerical modelling procedures which provide the necessary information about the physical parameters of the materials used and their respective impact on the output characteristics of the semiconductor devices (Lawal et al, 2025).

### 4.0 RESULTS

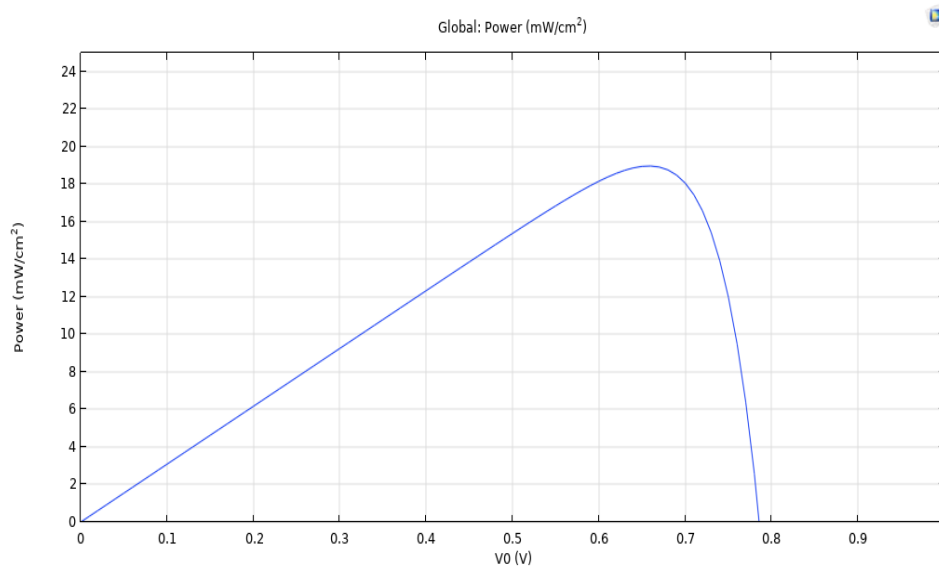
The perovskite solar cell (PSC) structure is designed to be used in the simulation as depicted in figure 1 showing the proposed architecture. The physical parameters of the PSC materials are contained in Table 1. In carrying out this simulation a constant input irradiance of 1000Wm<sup>2</sup> as found at AM1.5G at a temperature of 300K. Also, thermal velocities of 10<sup>7</sup> cm<sup>-s</sup> are granted to both the electron and hole while Shallow uniform acceptor density (N<sub>A</sub>) and donor density (N<sub>D</sub>) doping concentrations for KGeCl3 are being maintained at 10<sup>15</sup>cm<sup>-3</sup> in this simulation. A Current density of 31.02mA/cm<sup>2</sup> and an output power of 19.04mW/cm<sup>2</sup> was achieved as indicated in Figure 3 and 4 respectively.



**Figure 2.** Sequence in COMSOL Multiphysics (Lawal et al, 2025).



**Figure 3.** I-V Characteristics of Perovskite Solar Cell



**Figure 4.** P-V Characteristics of Perovskite Solar Cell

## 5.0 CONCLUSION

This work has examined the effectiveness and potential of C60 material as an electron transport with a combination of hole transport material in the composition of perovskite solar cells (PSC), while KGeCl<sub>3</sub> in the absorption layer. The absorption material used in this work was potassium germanide chloride (KGeCl<sub>3</sub>) and has shown great potential in the power conversion efficiency (PCE) of the PSC solar cell. However, the use of NiO as the hole transport material (HTM) in combination with C60 as electron transport material (ETM) has shown good output results of the PSC solar cells with a current density of 31.02mA/cm<sup>2</sup> at an open circuit voltage of 0.78V and an output power of 19.04mW/cm<sup>2</sup>

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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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## PHYSICAL AND CHEMICAL CHARACTERIZATION OF KUBAU TIN ORE KADUNA

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Bulk Density.

### ABSTRACT

*This study focuses on the physical and chemical characterization of Kubau tin ore located in Kaduna State, Nigeria, to assess its suitability for concentration and industrial applications. The study involved collecting seven representative samples from the Kubau area, followed by physical characterization, including specific gravity and bulk density measurements, and chemical analysis using X-ray fluorescence (XRF) spectrometry. The specific gravity of the ore averaged 7.29, indicating a high concentration of cassiterite, while the bulk density was found to be 2.50 g/cm<sup>3</sup>, suggesting some porosity. Chemical analysis revealed significant variability in SnO<sub>2</sub> content, with high-grade zones in Samples 4 and B (69.89 wt% and 55.51 wt%, respectively). Samples also showed impurities such as SiO<sub>2</sub> and Fe<sub>2</sub>O<sub>3</sub>, which would require gravity separation for silica and magnetic separation for iron. The study concludes that the high-grade tin ore in Kubau is suitable for industrial applications, such as tin smelting and alloy production, while lower-grade samples may be used in silica-based industries. Recommendations for further geological mapping, advanced mineralogical analysis, and optimization of beneficiation techniques are provided.*

### 1. INTRODUCTION

Tin ore, primarily composed of cassiterite (SnO<sub>2</sub>), is a significant mineral resource in Nigeria, with notable deposits in regions such as Jos Plateau and parts of Kaduna State. The mineralization of tin in these areas is tied to complex geological formations, notably the Younger Granites, which are rich in tin-bearing minerals such as cassiterite (Adebayo & Dada, 2018). Kubau, located within Kaduna State, is one of the sites where such mineralization has been identified, offering great potential for extraction and processing of tin ores (Mokwunye et al., 2020).

The characterization of tin ore is essential for determining its suitability for mining and beneficiation. Physical characterization involves the analysis of properties such as particle size distribution, specific gravity, and mineral composition, all of which influence the ore's behavior during processing (Tansel et al., 2017). For example, the particle size distribution of the ore plays a crucial role in gravity separation techniques, which are commonly employed for tin ore

beneficiation (Ejembi et al., 2019). These physical properties help in determining the most efficient processing methods for extracting tin.

Chemical characterization is equally important, as it involves the analysis of the elemental composition of the ore. This includes determining the concentration of tin, the presence of associated minerals, and identifying any impurities, such as iron or sulfur, which may affect the efficiency of extraction processes (Usman et al., 2020). The concentration of tin in the ore, as well as the presence of other elements, can significantly influence the ore's suitability for various refining techniques (Adebayo & Dada, 2018). Studies on tin ore from other Nigerian regions, such as the Jos Plateau, have helped in understanding the mineralogical composition of tin ores and in developing better methods for extraction and processing (Nwachukwu & Uzoma, 2018).

Geophysical surveys in Kaduna State have revealed linear structures that may indicate the presence of tin ore veins, providing further insights into the exploration potential of the region (Mokwunye et al., 2020). Additionally, the mineralogical and geochemical characterization of Kubau tin ore will enhance the understanding of its physical and chemical properties, which will inform future mining strategies and optimize processing methods.

This study, therefore, aims to provide a comprehensive analysis of the physical and chemical characteristics of Kubau tin ore in Kaduna State. By conducting detailed physical and chemical characterization, the study seeks to contribute to the efficient and sustainable extraction of tin from this region, which could enhance Nigeria's position in the global tin market.

## **2. MATERIALS AND METHOD**

The method for determining the physical and chemical characteristics of Kubau tin ore involved a straightforward approach. 8 samples was collected from a representative location in the Kubau area, Kaduna State. The sample was labeled with location details and stored in an airtight bag to avoid contamination during transport. In the laboratory, the sample was air-dried at room temperature to remove moisture. Physical properties such as specific gravity were measured using a density bottle method, where the sample's weight was compared with the weight of water displaced. The chemical composition of the sample was analyzed using X-ray fluorescence (XRF) spectrometry, which provided a detailed breakdown of tin content and other elements. This simple yet effective approach allowed for the characterization of Kubau tin ore, which is crucial for evaluating its suitability for beneficiation.

## **3. RESULTS AND DISCUSSION**

**Table 1.** Determination of Specific Gravity of Rock Sample

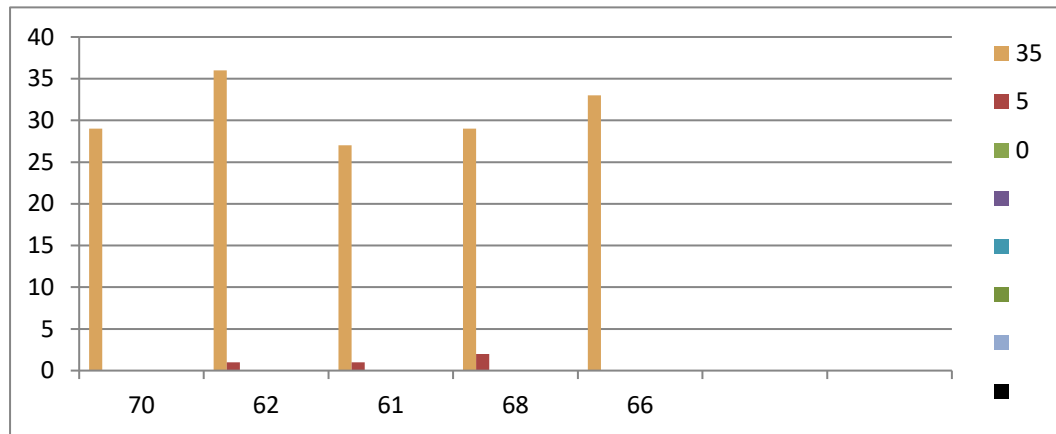
Test No.	1	2
Mass of bottle (W1)g	21.1	25.3
Mass of bottle + specimen (W2)g	63.2	67.7
Mass of specimen + bottle + water (W3)g	109.0	111.4
Mass of bottle + water (W4)g	78.48	80.62
Mass of water (W4-W1)g	57.38	55.32
Mass of water added to the bottle (W3-W2)g	45.8	43.7
Mass of specimen (W2-W1)g	42.1	42.4
Mass of water displaced by specimen (W4-W1) - (W3-W2)=(W)g	5.78	5.82
Specific gravity (W2-W1)/W	7.28	7.29
Average specific gravity		7.29

**Table 2.** Determination of Bulk Density of Rock Sample

Sample ID	1	2
Mass of specimen $W_1$ (g)	120.0	120.0
Mass of empty beaker ( $W_2$ )g	33.0	33.0
Mass of beaker + displaced water (g)	80.5	80.5
Volume of Specimen (V) $\text{cm}^3$	47.5	47.5
Bulk density ( $W_1/V$ ) $\text{g}/\text{cm}^3$	2.52	2.52
Average ( $\text{cm}^3$ )	2.54	

**Table 4.3.** Result from Chemical Analysis using XRF

S/N	Sample ID	Oxides%							
		SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	CuO	CaO	MgO	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	SnO <sub>2</sub>
1	Sample 1	23.425	11.586	0.102	0.682	0	4.699	14.67	14.074
2	Sample 2	13.941	15.065	0.151	0.748	0	3.089	15.039	12.875
3	Sample 3	64.945	4.315	0.033	0.463	0	23.659	1.521	0.259
5	Sample 4	12.637	3.969	0.124	3.698	0.769	6.964	0.319	69.886
6	Sample A	50.115	26.155	0.032	0.855	0	16.874	2.097	0.233
7	Sample B	19.006	3.523	0.004	2.632	1.212	4.778	10.184	55.511
8	Sample C	59.743	15.311	0.052	0.895	0	14.781	4.669	1.035



**Figure 1.** Chart Showing the Oxide Concentration (wt %) in Samples

### 3.1 Gravity Concentration Criterion

SG of Cassiterite = 7.29, SG of quartz (SiO<sub>2</sub>) = 2.58, SG of fluid = 1.0, SG of hematite (Fe<sub>2</sub>O<sub>3</sub>) = 5.2  
Using;

$$CC = \frac{p_h - p_f}{p_l - p_f} \quad CC = \frac{7.29 - 1.0}{2.58 - 1.0} = \frac{6.29}{1.58} = 3.98$$

$$CC = \frac{7.29 - 1.0}{5.2 - 1.0} = \frac{6.29}{4.2} = 1.50$$

The physical and chemical properties of Kubau tin ore were analyzed to evaluate its suitability for concentration and industrial applications. The specific gravity of 7.29 (Table 4.1) confirms the presence of dense minerals, primarily cassiterite (SnO<sub>2</sub>), which has a typical specific gravity of 6.8–7.1. This high specific gravity indicates that the ore is rich in tin. However, the bulk density of 2.50 g/cm<sup>3</sup> (Table 4.2), which is significantly lower than the specific gravity, suggests that the ore is somewhat porous. This porosity is likely due to the presence of gangue minerals or microfractures. The bulk density was determined using the water displacement

method, which provided accurate volume measurements, and the consistent results (ranging from 2.49 to 2.50 g/cm<sup>3</sup>) enhance the confidence in the data.

Chemical analysis through X-ray fluorescence (XRF) (Table 4.4) revealed significant variability in the ore's composition. The SnO<sub>2</sub> content ranged from 3.45 wt% in Sample A to 69.89 wt% in Sample 4, indicating high-grade cassiterite zones. Samples 4 and B, with SnO<sub>2</sub> contents of 69.89 wt% and 55.51 wt%, respectively, suggest the presence of a tin-rich vein or zone within the Kubau deposit. These samples were collected from coordinates near 8°13'15.4'' E, 10°52'05.3'' N (Sample 1) and 8°13'13.4'' E, 10°52'05.8'' N (Sample 2). Conversely, Samples 3, A, and C had lower SnO<sub>2</sub> concentrations (5.23 wt%, 3.45 wt%, and 8.76 wt%, respectively), with high SiO<sub>2</sub> contents (64.95 wt%, 60.12 wt%, and 58.34 wt%), indicating the dominance of silicate gangue minerals like quartz. Sample A also showed a high Fe<sub>2</sub>O<sub>3</sub> content (26.16 wt%), suggesting the presence of iron-bearing minerals like hematite or magnetite, which may require magnetic separation during beneficiation. Additionally, trace elements such as Nb<sub>2</sub>O<sub>5</sub> (0.05–0.30 wt%) and Ta<sub>2</sub>O<sub>5</sub> (0.03–0.25 wt%) were present in Samples 4 and B.

To assess the suitability of the ore for beneficiation, the physical and chemical properties were integrated. The high specific gravity (7.29) aligns with the gravity concentration criterion, suggesting the possibility of using gravity separation to separate gangue minerals like SiO<sub>2</sub> and Fe<sub>2</sub>O<sub>3</sub>. The result for SiO<sub>2</sub> removal by gravity concentration showed a promising possibility (Wills, 2016), while the removal of hematite indicated a lower likelihood of success using gravity concentration but suggests that magnetic separation could be a more effective method. Samples 4 and B, with high SnO<sub>2</sub> content (above 50 wt%), meet the requirements for high-grade tin concentrates suitable for applications like soldering, tin plating, and alloy production (e.g., bronze). The high purity of these samples minimizes the need for extensive refining, reducing processing costs. These findings are validated by comparing them with expert decisions and adjusting the rules accordingly to ensure that the recommended beneficiation methods align with expert knowledge.

#### **4. CONCLUSION AND RECOMMENDATION**

This study analyzed the physical and chemical properties of Kubau tin ore to assess its potential for beneficiation. The specific gravity of 7.29 confirmed the presence of dense tin-bearing minerals like cassiterite, while the bulk density of 2.54 g/cm<sup>3</sup> indicated slight porosity due to gangue minerals. XRF analysis showed significant variability in SnO<sub>2</sub> content, with high-grade zones in Samples 4 and B, containing 69.89 wt% and 55.51 wt% SnO<sub>2</sub>, respectively. Silica and iron impurities were also identified, suggesting the need for gravity separation for silica and magnetic separation for iron. The high SnO<sub>2</sub> content in certain samples indicates their suitability for tin smelting, while low-grade samples are more appropriate for silica-based industries.

Recommendations include further geological mapping to locate tin-rich veins, advanced mineralogical analysis to explore co-extraction possibilities, optimization of gravity and magnetic separation techniques for beneficiation, and the utilization of low-grade samples in industries like glass, ceramics, and steel 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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## DESIGN AND INSTALLATION OF A PHOTOVOLTAIC POWER SYSTEM WITH SURGE PROTECTIVE DEVICES

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### Abstract

*The paper considered the design and installation of a solar power system with full surge protection unit that provides the minimal electric power needed to supply an office block in Federal Polytechnic Kaltungo, Gombe, Nigeria. The design process involved the selecting and determining the power consumption of some specific appliances that needed to be powered within the building. The power requirements of the photovoltaic (PV) system components were determined via computation to match the total power requirements of the 5.975 kVA load. The location of the building under consideration falls under the "medium" exposure level and the distance between the PV array and the inverter/charge controller unit was greater than 10m, therefore, two type 2 Direct Current (DC) Surge Protective Devices (SPDs) were used at the DC side. Additional AC type 2 SPDs were installed at the inverter's output, because the building was not equipped with direct Lightning Protection System (LPS). The installed SPDs can only mitigate the effect of indirect lightning strike on installations within the PV system, but cannot prevent external damage on the PV array by direct lightning strike. Therefore, a lightning risk assessment table was used to determine the need for lightning protection system installation in the building and the result justified the LPS installation requirement.*

### 1. INTRODUCTION

One of the major challenges bedeviling the establishment of new higher institution of learning in Nigeria is the problem associated with lack of adequate and sustainable electric power supply. More often, most of the buildings in such institutions are either powered by low-power

diesel engines or lower-power petrol generators. The running costs of these fossil fuels can never be sustained, considering the soaring increase in their prices, the fluctuating meagre allocations of overhead costs from the federation account to such institutions and the meagre internally-generated revenue accrued by the institutions, considering the number of students and infancy factor.

The study is expected to tackle some of the electric power challenges encountered in similar newly-established institutions, if such initiatives could be extended to other buildings in each institution. With a very good system design and full protection mechanism in place, the initiative will provide a lasting solution to the aforementioned challenges.

Photovoltaic power generation is the process of generating electricity directly from sunlight; (Ifeanyi-nze and Okayim, 2022). Most photovoltaic systems being used in a variety of applications are essentially stand-alone (Alhousni et al., 2022). A photovoltaic power system consists of six components that are wired together to form a fully functional stand-alone system capable of generating and supplying electric power (Adebisi, et al., 2023). The installation of the power system that can provide continuous electricity supply to the school's building, providing solutions to; challenges of power outages, cost of fuelling generator, noise pollution and global warming is part of the motivation to the research.

Mahmood (2019) designed and simulated a stand-alone PV system that will provide electric power to an electronic and communication engineering laboratory in Al-Nahrain University, Iraq. The author had done justice to the design and simulation process, although, the research did not consider the power requirements of an inductive loads, as most of the devices in the laboratory are non-inductive loads. However, there might need to consider the supply of power to the ceiling fans or an air-conditioner, considering Iraq being a hot temperate region.

The design of stand-alone solar energy system was implemented by Auwal and Muhammad, 2021 for rural dwellers in Zamfara State of Nigeria. The duo used MATLAB/Simulink R2020a to simulate the system, although, there was no practical implementation of the system. The design has the limitation of failing to consider safety and protection of the system.

There are a host of related literature from 2015 to date that had worked on stand-alone solar power system without considering the safety and protection of the system. Such literatures include: design of a stand-alone photovoltaic system for a Bauchi residence by Guda and Aliyu, 2015; a report by Quak (2018) to aid the generation and use of solar energy in sub-Saharan Africa with the view of meeting the rising demand of electricity in the region; Evans, Umoh and Petters (2022) considered the mathematical models for the design of PV solar power system, there authors were not explicit on the protection system used.

## **2. PV POWER SYSTEM DESIGN**

### **2.1 Solar PV Module**

Four 25V, 200W solar panels are proposed to be used for the research. The six panels were connected in series to increase the quantity of voltage supplied to a hybrid inverter. The sizing of the solar module depends on affordability, load demand, availability of sun radiation and temperature based on location.

The parallel connection combines the amount of current generated by the two panels, thus increasing the total current supply. The increased current enables faster charging of the

batteries. Therefore, the higher the current, the faster the battery charging process, although, the type of charge controller used also plays an important role on the battery charging. When the solar modules are in large number, they can be connected to form a parallel-series arrangement called solar PV array. The total number of PV modules in an array can be determined using Equation (1).

$$N_{tm} = N_{pm} \times N_{sm} \quad (1)$$

where,  $N_{pm}$  is the number of modules connected in parallel and  $N_{sm}$  is the number of modules connected in series

## 2.2 Battery Bank Sizing

The battery type recommended for use in solar PV power system is deep cycle battery, specifically designed such that even when it is discharged to low energy level it can still be rapidly recharged over and over again for years. The battery should be large enough to store sufficient energy to operate all loads at night, cloudy, rainy and dusty days.

The battery bank consists of two or more even connection of the deep cycle batteries in parallel-series arrangement, depending on requirement. In this research, four 12V, 200AH batteries are proposed to be used. The size of the battery bank can be determined using Equation (2).

$$\text{Size of battery bank} = N_{bs} \times N_{bp} = 2 \times 2 = 4 \text{ batteries} \quad (2)$$

where,  $N_{bs}$  is the number of batteries connected in series and  $N_{bp}$  is the number of batteries connected in parallel,

## 2.3 Inverter Sizing

An inverter is used in the PV power system when an ac power output is needed. The input rating of the inverter should never be lower than the total power of the different loads and must have the same nominal voltage as that of the battery bank. In practice, the capacity of the inverter is taken to be the sum of the total power of all loads running simultaneously and 3 times the total power of all inductive loads with large surge currents. Thus, the inverter power is determined using Equation (3).

$$P_{inv} = 1.25(P_{sum} + 3P_{ind}) \quad (3)$$

where  $P_{inv}$  is the power of the inverter in VA,  $P_{sum}$  is the sum of power of all loads running at the same time, and  $P_{ind}$  is the power of all inductive loads with high starting torque.

The 1.25 is a safe factor signifying an increase of 25% on the total capacity of the load. The load profile of the building will determine the size of the inverter to be used as depicted in Table 1.

Since most inverters are rated in kVA, the total load profile in Watts obtained from Table 1 can be converted to kVA, using a nominal power factor of 0.8, as follows:

$$P_{inv}(kVA) = 0.8P_{inv}(kW) = 0.8 \times 4.87 = 5.975 \text{ kVA}$$

Therefore, a 24V, 6 kVA hybrid inverter was chosen to supply the loads. It is important to note that the three times multiplier and the safe factor was not considered in the above calculations.

This is due to the fact that, not all loads will be connected to the PV system simultaneous. Consequently, the ratings of the components of the solar PV power system will be determined, based on the total load profile, cost and availability of the component parts in the market.

**Table 1.** Daily Load Profile of the Building

Load	Quantity	Power Rating (Watt)	Daily Usage Hours	Daily Energy Consumption (Wh)
Ceiling Fan	4	70	3	840
Photocopier	2	1000	0.5	1000
Printer	3	500	0.5	750
Electric water pump	1	1500	1	1500
Computer system	3	65	4	780
Total Load Profile				4870

## 2.4 Photovoltaic Surge Protection

Kaltungo local government area, located in southern area of Gombe State of Nigeria is characterized by occasional lightning strikes during the rainy season. In 2020, an unreported lightning strike hit the First Bank branch office, located in Kaltungo town, leaving internet communication facilities and host of networked desktop computers completely damaged. Therefore, full protection of the grid- and generator-tied PV power system against lightning surge, transient overvoltage and excessive current that may emanate from generator switching operations, voltage fluctuations or short circuit is needed to be designed and installed.

### 2.4.1 PV Rooftop Installation

Based on the exposure of the building location, the maximum discharge current ratings of the SPD are determined by a risk analysis shown in Table 2.

**Table 2.** Recommended Maximum Discharge Current,  $I_{max}$  According to Location

	Exposure Level		
	Low	Medium	High
Building Environment	Building located in an urban area of grouped housing	Building located in a plain	Building where there is a specific risk: pylon, tree, mountainous region, wet area or pond, etc.
Recommended $I_{max}$ Value (kA)	20	40	65

*Source: Schneider Electric – Electrical Installation Guide: Overvoltage Protection (2015)*

Since the location under consideration falls under the “medium” exposure level and the distance between the PV array and the inverter/ unit was greater than 10m, two type 2 SPDs with 40kA rating were selected. The connection of the PV array to the charge controller/inverter unit, with surge protections is as shown in Figure 2.

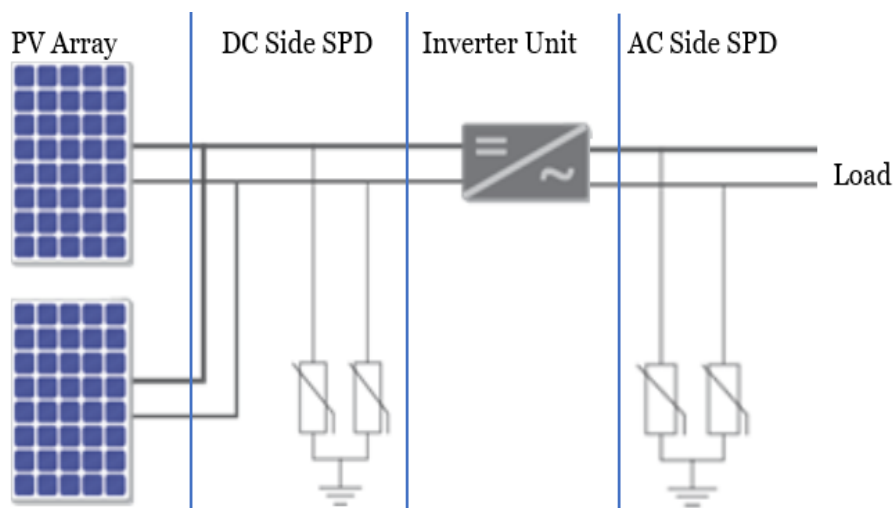


Figure 2. SPD Implementation in a PV System

There was no need to use SPD close to the inverter's DC input side, because the inverter has an in-built surge protection system.

### 3. RESULTS AND DISCUSSION

#### 4.

#### 4.1 PV Power System Components

The simulated results of the PV module characteristic curves with the output current against the voltage (I-V curve) and the output power plotted against the voltage (P-V curve) for different solar irradiances and module cell temperatures, using MATLAB/Simulink, are presented in Figures 3 (a) & (b) and 4 (a) & (b) respectively.

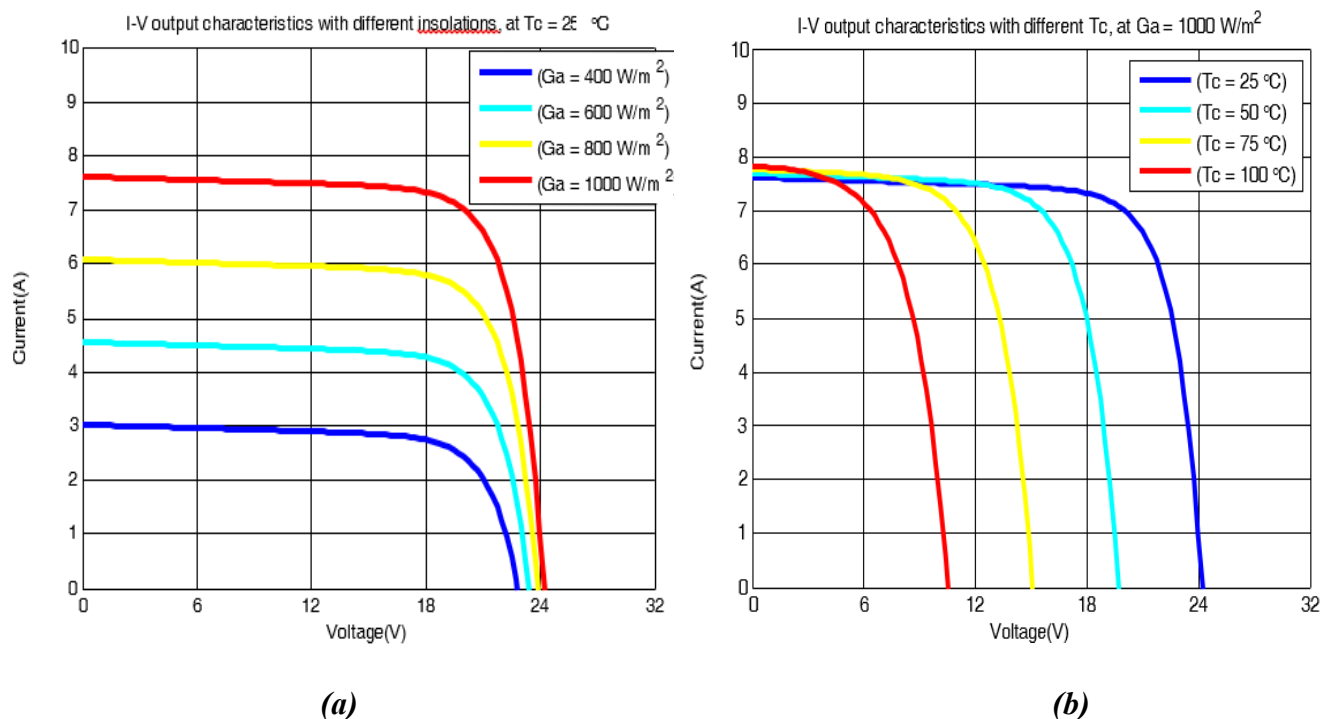
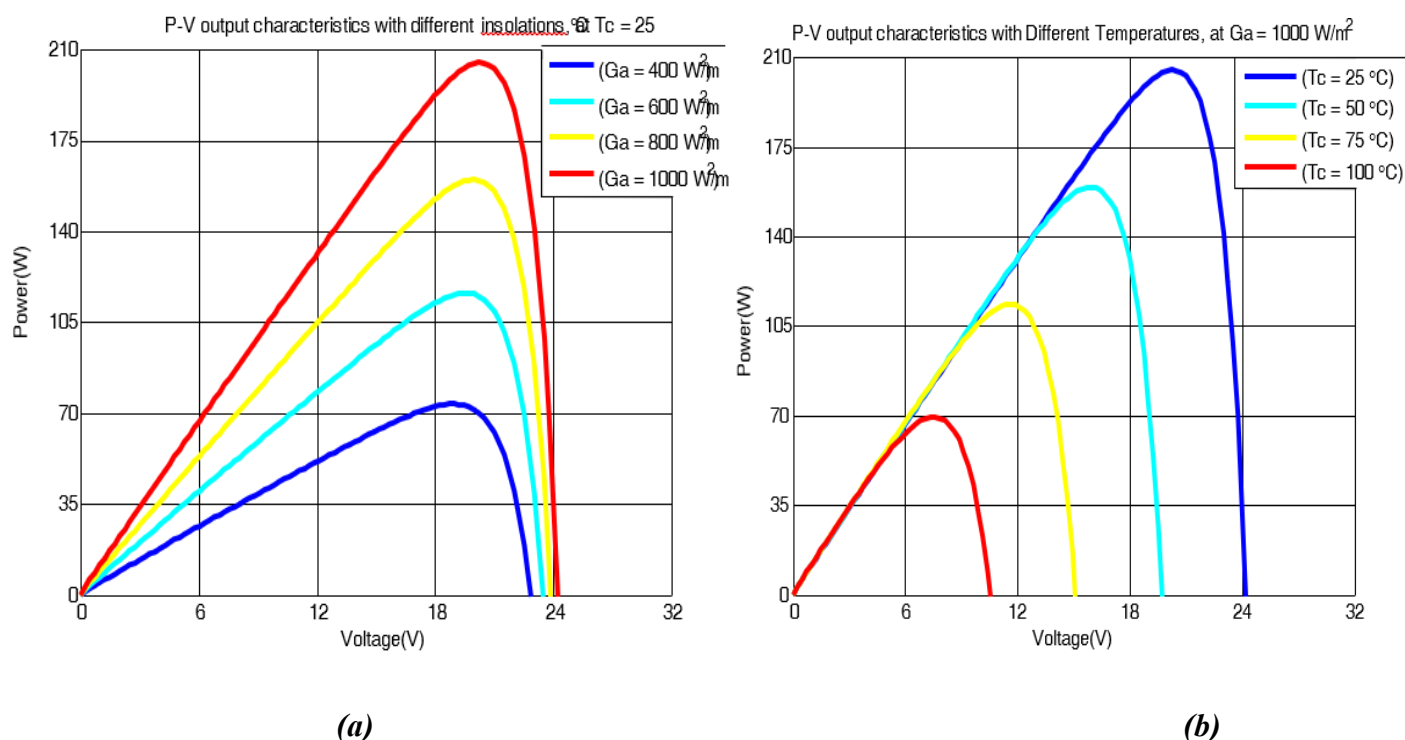


Figure 3. (a) I-V Curve at Different Solar Irradiances ( $T_c = 25^\circ\text{C}$ ) (b) I-V Curves at Different Cell Temperatures ( $G_a = 1000\text{W}/\text{m}^2$ )



**Figure 4.** (a) P-V Curve at Different Solar Irradiations ( $T_c = 25^\circ\text{C}$ ) (b) P-V Curve at Different Cell Temperatures ( $G_a = 1000\text{W}/\text{m}^2$ ).

The nonlinear nature of the PV cell is apparent as shown in Figures 3 to 4. The output current and power of PV cell depend on the cell’s terminal operating voltage and temperature, and solar insolation as well. It can be concluded from Figures 3(b) and 4(b) that with increase in working temperature, the short-circuit current of the PV cell increases, whereas the maximum power output decreases. In as much as the increase in the output current is much less than the decrease in the voltage, the net power decreases at high temperatures. On the other hand, it can be concluded from Figures 3(a) and 4(a) that with increase in solar insolation, the short-circuit current of the PV cell increases, and the maximum power output increases as well. The reason is that the open-circuit voltage is logarithmically dependent on the solar irradiance and the short-circuit current is directly proportional to the radiant intensity.

#### 4.2 Surge Protection

The surge protective devices are used in photovoltaic power systems for protection against transient overvoltage caused by indirect lightning stroke and switching operations. According to the IEC 62305 guide for safe installation of SPDs, a type 2 SPD is placed on the DC output between the inverter and solar panels array if their separation distance is greater than 10 meters. The separating distance between array and the inverter was measured to be more than 10 meters, so two type 2 SPDs were installed. Similarly, the separation distance between the load and the inverter was found out to be greater than 10 meters, therefore, a single type 2 SPD was installed at the AC side of the inverter.

The total solar power output voltage of the system is 150VDC, therefore, a NOVARIIS brand SPDs with the specifications shown in Table 3 were installed at the DC side of the inverter.

At the inverter’s AC side, a NOVARIIS SDD1-50-275 SPD was installed close to the inverter. It has the electrical specifications shown in Table 4.

**Table 3.** Specifications of SPD Installed at the DC Side of the Inverter

Maximum continuous voltage DC	$U_c$	155VDC
Maximum discharge current (8/20 $\mu$ s)	$I_{max}$	40kA
Nominal discharge current (8/20 $\mu$ s)	$I_n$	20kA
Voltage protection level (3kA, 8/20 $\mu$ s)	$U_p$	<370V
Response time	$I_A$	<5ns

**Table 4.** Specifications of SPD Installed at the AC Side of the Inverter

Maximum continuous voltage AC	$U_c$	275V/50Hz
Nominal voltage	$U_o$	230V/50Hz
Maximum discharge current (8/20 $\mu$ s)	$I_{max}$	50kA
Nominal discharge current (8/20 $\mu$ s)	$I_n$	20kA
Voltage protection level (3kA, 8/20 $\mu$ s)	$U_p$	<800V
Response time	$I_A$	<5ns

### 4.3 Lightning Protection System

A design procedure to determine the need for lightning protection system installation in the building was conducted using a lightning risk assessment table by simply entering the building's dimensions. The computed results are depicted in Table 5.

**Table 5.** Lightning Risk Assessment

$A_e(km^2)$	$N_c$	$N_d$	LPS Requirement
0.01266	0.0015	0.04084	INSTALLATION REQUIRED

Where  $A_e$  is the equivalent collective area of the building,  $N_c$  and  $N_d$  are the tolerable and expected lightning strike frequencies respectively. The tolerable lightning frequency  $N_c$  was found out to be less than the expected lightning strike frequency  $N_d$ , therefore, an LPS installation is required on the building.

## 5. CONCLUSION

There were no lightning protection systems in most of the buildings within the Institution, which necessitates the need for the type 2 SPD installations when mounting the PV system. The essence of positioning the type 2 SPDs at various points throughout the PV power system is to protect the inverter and other system components and prevent the spread of overvoltage from indirect lightning strike. The existing PV installations either lack proper SPD design that will match the system requirements or no SPD installed at all.

In conclusion, the installed SPDs can only minimize or mitigate the effect of indirect lightning strike on the PV installations within the building, but cannot prevent external damage on the PV array that may be caused by direct lightning strike. Therefore, there is need for installation of a complete lightning protection system in the building as determined from the lightning risk assessment in Table 4.

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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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## FEASIBILITY STUDY AND CHARACTERIZATION OF UGBOHA RIVER FOR HYDROELECTRIC POWER PLANT

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### Abstract

*This paper presents a feasibility study and characterization of Ugboha (Edoha) river situated at Esan South East Local Government Area of Edo State, Nigeria, for hydroelectric power plant. The study was done on the need to mitigate the inadequate and epileptic electricity supply being experienced by the National Institute of Construction Technology and Management (NICTM), Uromi, Edo State, Nigeria, a Federal Polytechnic situated between Amendokhian community and Ugboha community in Edo State, Nigeria. The use of backup diesel generating plants has increased the overall operating cost of the polytechnic due to the need to purchase fuel and the associated maintenance cost of the plants. The method adopted in this research was the determination of the discharge (flow) rate via the floating technique, while the surface and the mean velocities of the river, the kW derivability, irrigation potential to the communities' farmers and flood control in the Local Government Area of the state were evaluated. The Ugboha (Edoha) river has a flow rate of 1.75 m<sup>3</sup>/s with estimated head of 4.3 m and hydroelectric power generating potential of about 55.31 kW. The feasibility work and characterization of the Ugboha (Edoha) river was significant as it will aid the commencement of detailed project report (DPR) that will highlight detailed study of hydrology and geology, environmental impact assessment, flood control in the area and weir structure for hydropower plant on the Ugboha (Edoha) River.*

### 1. INTRODUCTION

Energy is distributed across the surface of the earth; according to the law of conservation of energy, it can neither be created nor destroyed; but can be transformed from one form to another. At every particular time, there is enough energy for human consumption, but the challenges of converting it from its existing form to a useful form like electricity has not been fully addressed; if power for all is going to be a reality. A power plant that utilizes the potential energy of water at a high level for the generation of electrical energy is known as hydroelectric power and is a clean and environmentally friendly renewable energy source. Its multi-

functional capacity in the area of electricity generation, farm irrigation, flood control, etc. cannot be overemphasized.

Electricity has been one of the major catalysts that drive any viable economy as it is an inevitable input required for the technological and socioeconomic development of a nation (Oliver, 2002). Nigeria being a developing country needs steady economic drive and this can be achieved by stable electricity supply to the citizens of the country. The Nigeria grid utilizes hydro and thermal electricity generation methods. The hydroelectricity generation method is dated back to 19<sup>th</sup> century, first in Northumberland, England in 1878 and today, quite a good number of hydropower plants have been developed across the globe with these plants providing 2,998 billion kilowatts hours of clean and renewable energy in 2006, approximately 20 % of the worldwide (Painted Sky RC & D Council Incorporation, 2001).

The Nigeria power supply dated back to 1896 when electricity was first produced in Lagos, fifteen years after its introduction in England (Niger Power Review, 1985). From that time till now, Nigeria generation capacity fluctuates around 2500 MW and 5000 MW to support the country's socioeconomic growth and development (Kela et al., 2001). This range of megawatts generation, over decades has affected the socioeconomic growth and development of the country. The total installed capacity of power generation in this country has fallen below the country's electricity demand because of overwhelming population growth (Odje, Uhumwangho and Okedu, 2018). To achieve sustainability, reliability and a decentralized electricity supply in Nigeria which has chunk of its populace living in remote and isolated rural communities with no access to electricity and over the years, renewable energy sources have been appraised as one of the guaranteed technology that must be aggressively harnessed since some of these rural areas located far from National Grid have enormous unexploited hydro energy sources e.g flowing rivers, streams, water fall, biomass, solar and wind energy amongst others capable of bridging the energy gap in the country (Odje, Uhumwangho and Okedu 2018; Olayinka, 2011).

Nigeria as a country is yet to substantially harness the huge potential power available with small or micro hydro schemes despite its huge electricity supply available in the country is characterized with epilepsy in nature. The electric energy supply deficit in the country has caused serious and high load shedding and rationing in the country which has impacted socioeconomic growth and development negatively. This is one of the major reasons for the recent economic quagmire in Nigeria as a country facing now, where companies can no longer sustain production cost and paying due to high cost of production of fuel purchase in powering generating plants in the various companies to sustain production. According to Okoye, Kassen and Gokcekus (2023). Nigeria faces challenges in meeting the electricity demand of its rapidly growing population despite being blessed with power production sources abundantly. The existing large gap between energy demand and supply in the Nigeria electricity grid has been obvious and worrisome to stakeholders in the power industry and today a bridge is needed. No wonder, according to Ravneet and Jayati (2013). Stated that renewable energy is a sustainable, clean source of energy and its development is thriving due to failure of existing generation to meet load demands and its growth, inefficiency of existing grid system, shortfall in fossil energy and adverse environmental impacts.

To maintain stable power supply in Nigeria today, renewable energy sources are key factors. Hence, electricity generation from the flow of rivers is a clean and environmentally friendly renewable energy source (Ozigis et al., 2019). Hydropower plant is currently the least expensive source of electric power and is much cleaner than power generated from fossil fuel

(Ozigis et al., 2019). In a small flowing river or stream, small hydropower is considered as the best appropriate method of generating renewable energy (Hatata et al., 2019). Hydropower plant systems are classified as large-scale hydro plants: over 100 MW capacity, Medium scale hydro plants: 10 -100 MW, small hydro plants less than 10 MW, mini-hydro plants: 1000 – 100 kW, Micro-hydro plants: 5 – 100 kW and Pico-hydro plants: less than 5 kW (Paish, 2002a; Paish, 2002b). Small hydropower schemes have been on the front burner for cleaner energy sources that can fast-track rural electrification considering the huge unharnessed rivers and streams in the rural settlement (Penche, 1998). This huge unharnessed rivers and streams in Nigeria can play a huge support to the National Grid, if properly harnessed.

The roles of electric energy and its application in socioeconomic development become obvious as they continually increase with the growing population of the country. Hydroelectricity in Nigeria is the most used type of energy for power generation in that Nigeria’s geographical area favours its usage (Fakehinde et al., 2019). Nigeria is enormously blessed with renewable energy resources, as presented in Table 1. Therefore, this paper aims at determining the river's flow rate, availability of hydropower potential, feasibility of harnessing and characterization of the Ugboha (Edoha) river for small and micro – hydroelectric power generation.

**Table 1.** Energy Potential in Nigeria (Sambo, 2009).

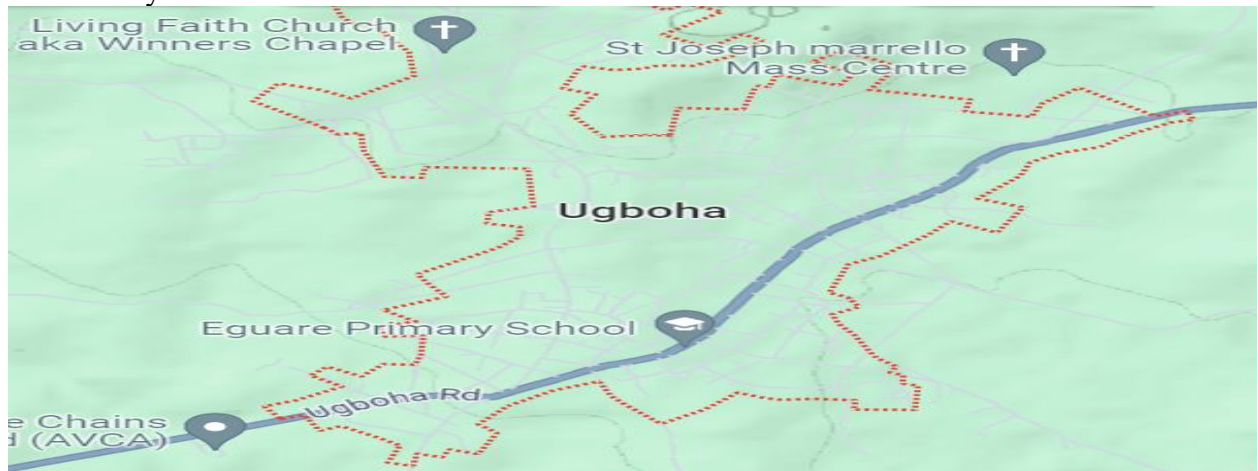
Resource type	Hydropower		Solar Radiation	Biofuel			Wind
	Large Hydropower	Small Hydropower		Fuel Wood	Animal Waste	Crop Residue	
Reserves	11,550 MW	3,450 MW	3.5 – 7.0 kWh/m <sup>2</sup> -day	13,071,464 Hectares	61 million tonnes/y	8.3 million tonnes/y	2 – 4 m/s (annual average)

### 1.1 Brief Description of Ugboha Community

Ugboha is a town in Esan south East Local Government of Edo State, Nigeria (Okosun et al., 2000). Ugboha lies on the geographical coordinate of latitude 6° 45’ N, 6° 28’ E. The correct name is Owoha. Although the population was given as 3,003 (Three thousand and three) in the 1993 census, the more accurate figure was likely to be nearer to 5000 (five thousand) than anything else, for Eguare, Emuado, Idumu-Ihaza, Uzogbon, Inemen and Amalu without Idegun and Otokhimin have a population of 4,480 (Four thousand, four hundred and eighty) people (Okojie, 2022). Ugboha is organized into several key districts. The main districts are Eguare and Emuado, which play significant roles in the town’s traditional and administrative structure.



**Figure 1.** A Map showing NICTM situated between Amendokhian Community and Ugboha Community



**Figure 2:** A Map showing the location of Ugboha Community



**Figure 3.** A Map showing the Entire Esan Land in Edo State, Nigeria

## **2. MATERIAL AND METHODS**

This section of the research paper presents the materials used in the research and the method adopted as shown 2.1 and 2.2 respectively.

### **2.1 Materials**

The tools and equipment used are GPRS, measuring tape, stop watch, 100 m twine rope, 100 m chain meter, 20 numbers of wooden float, pen, notebook, camera, two chain men, qualified surveyor, civil engineer and electrical engineers.

#### **2.1.1 Brief Description of Ugboha (Edoha) River**

The Ugboha River cuts through Ugboha to Ubiaja and through Oria River in Esan South East Local Government Area of Edo State, Nigeria. The Ugboha town lies on the geographical coordinate of latitude 6°28' E. Ugboha River is also called Edoha River, it flows into Ubiaja river to Oria river and then to Uzea river and then, to River Niger. Figure 2 and 3 shows the Google map location of Ugboha and Esan South East Local Government Area in Edo State, Nigeria respectively.

## **2.2 Method**

The float technique was adopted as a method to determine the flow rate of the river at estimated time and other parametric equations were adopted to calculate the available potential power and the river head.

### **2.2.1 Determination of the River Flow Rate**

The Ugboha River, also known as Edoha River, the flow rate measurement was achieved by employing the “Float Technique using a weighted piece of light wood.” This technique is to determine the duration it will take an object to float at specified distance in the river (Bartram and Balance, 1996). The float technique was to measure the surface velocity and the cross-sectional area at a selected spot of the river (Odje, Uhunmwangho and Okedu, 2018). The following were done at the river site:

- i. The start and end points of the reach were noted and marked-out
- ii. A piece of wooden measuring 0.5 m by 0.3 m by 0.02 m was dropped into the river to float from the start point to the end point already marked-out
- iii. Records of time was taken by a stop watch as the object crosses the start point marked and stop when it crosses the end point marked.
- iv. The float processes were repeated for ten (10) times using two (2) wooden floats at the same time at different points to see the current at different points of the river and the different times recorded were documented and the average time determined.
- v. The river’s width at the end point and calibration of the width into subdivision as well will be done to determine the corresponding river’s depth of each sub-division.

The Ugboha (Edoha) River’s discharge rate was determined by the surface velocity which is a ratio of the distance traveled by the wooden float to the time it takes the wooden float to travel such distance (Odje, Uhunmwangho and Okedu, 2018):

$$V_{surface} = \frac{d}{t_{av}} \text{ m/s} \quad (1)$$

where d = distance,  $t_{av}$  = average time.

$$V_{mean} = C * V_{surface} \quad (\text{m/s}) \quad (2)$$

where C is a factor that takes care of the nature of the river bed, C = 0.6 for rough bed and C = 0.9 for smooth bed.

The river discharge rate:

$$Q = V_{mean} * A \quad \text{m}^3/\text{s} \quad (3)$$

The potential output power is given as:

$$P_o = g * H * Q * \eta \quad \text{kW} \quad (4)$$

where  $P_o$  is the potential output power in kW and  $\eta$  is the overall efficiency of the hydropower.  $H$  is the available head in meters,  $Q$  is the design discharge rate in  $\text{m}^3/\text{s}$  and  $g$  is the acceleration due to gravity given as  $9.8 \text{ m/s}^2$

### 3. RESULTS PRESENTATION AND ANALYSIS

The river discharge (flow) rate measured using floating technique earlier mentioned in this research is presented with the cross-sectional area of the river Edoha (Ugboha River).

**Table 2.** Ugboha River Flow Measurement Data taken from May - July, 2024 with Travel Distance of 20 M

Number of Trials	Travel Time T(secs)
1 <sup>st</sup>	32.10
2 <sup>nd</sup>	32.00
3 <sup>rd</sup>	35.05
4 <sup>th</sup>	34.16
5 <sup>th</sup>	34.58
6 <sup>th</sup>	34.40
7 <sup>th</sup>	35.01
8 <sup>th</sup>	35.00
9 <sup>th</sup>	35.40
10 <sup>th</sup>	35.02

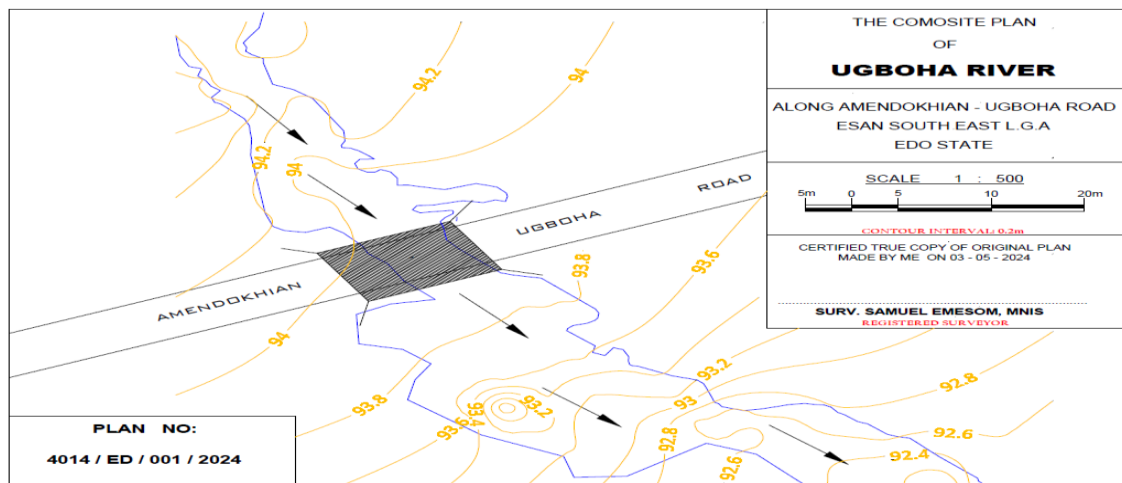
The cross-sectional area of the Ugboha River is presented as follows:

**Table 3.** Ugboha River Cross-Sectional at 5.0 M Intervals

S/N	Average River Width (m)	Average River Depth (m)	Area of the River ( $\text{m}^2$ )
0	0.00	0.00	0.00
1	8.20	1.26	47.68
2	7.17	1.28	37.10
3	8.56	1.27	42.08
4	9.96	1.35	47.26
5	11.41	1.48	54.43
6	13.90	1.60	66.46
7	15.38	1.63	75.68
8	22.09	1.79	115.59
9	19.50	1.85	101.92
10	18.10	1.96	95.57
11	22.70	2.09	118.72

The records in Table 3 show the sharpness of the Ugboha (Edoha) River bed as shown in Figure 3. The various areas associated with the various depths and widths of the river are shown in Table 3. The various areas were obtained through the bathymetric survey which covers the determination of the depths of the Ugboha (Edoha) River. Also, the hydrographic survey covers both bathymetric survey and the topographic survey which is the collection of the existing

points and features along the coaster lines. The Ugboha River's surface and mean velocities are obtained by applying equation 1 and 2 to the documented records using tolerance of 0.6 and  $t_{av} = 34.27$  s.



**Figure 3.** Ugboha (Edoha) River Bed Sharp at Ugboha Community, Esan South L.G.A, Edo State, Nigeria.

The Ugboha River discharge rate was gotten using equation 3 as  $Q = 1.75 \text{ m}^3/\text{s}$  and the potential power generation estimated from the Ugboha (Edoha) river using equation 4 at efficiency of 75 % with net head of 4.3 m of the river, the would be output:  $P_{\text{output}} = 55.31 \text{ kW}$ . The viability of the Ugboha River is obvious from the power output of about 55.31 kW and also, the Ugboha community; the majority are farmers who need irrigation in their farms, which the micro-hydroelectric plant will also serve. The Ugboha and Amendokhian communities have been having prolonged power fluctuation and failure which affects the tertiary institutions such as the National Institute of Construction Technology and Management (NICTM), Uromi which is situated between these communities. The feasibility analysis and the characterization of the Ugboha River are significant to the NICTM, Uromi and the immediate communities (Ugboha and Amendokhian). Additionally, the river can also serve as erosion collector from the NICTM, Uromi and the immediate communities if proper land scalping and erosion control is implemented. The various sections of the Ugboha (Edoha) River are presented in plate 1 to 6.



**Plate 1.** Shallow Section showing the Bed Sharp and Current of the Ugboha (Edoha) River



**Plate 2.** Side View of Ugboha (Edoha) River



**Plate 3.** Section of the Ugboha (Edoha) River



**Plate 4.** Water level of the Ugboha (Edoha) River



**Plate 5.** Sectional Depth of the Ugboha (Edoha) River



**Plate 6.** A Curve Section of the Ugboha (Edoha) River

#### **4. CONCLUSION**

The research presents the feasibility study and characterization of the Ugboha (Edoha) River for micro-hydropower plants. The research has demonstrated that the Ugboha (Edoha) river can generate about 55.31 kW of electric power at a flow rate of 1.75 m<sup>3</sup>/s and head of 4.3 m. For a more detailed and accurate flow rate measurement, standard current meter should be used instead of the wooden float technique adopted in this research. Also, a lengthier hydrological data over a wide period of time should be considered to further improve the accuracy of the flow rate measurement of the Ugboha (Edoha) river as well as the potential of the river for hydroelectric power generation to ascertain its accurate viability and potential for irrigation and flood control in the area.

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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 COMPARATIVE ANALYSIS OF LIQUEFIED PETROLEUM GAS (LPG) AND COMPRESSED NATURAL GAS (CNG) AS ALTERNATIVE FUELS FOR INTERNAL COMBUSTION ENGINES

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### Abstract

The global call for cleaner and more economical fuels has renewed interest in alternative fuels such as Liquefied Petroleum Gas (LPG) and Compressed Natural Gas (CNG). This study presents a comprehensive experimental comparison of LPG, Petrol (Gasoline), and CNG as fuels for internal combustion engines, focusing on combustion rate, energy efficiency, emissions, and cost effectiveness. Results showed that Petrol recorded the fastest combustion time (32 min/kg), followed by LPG (75 min/kg) and CNG (97 min/kg). Energy analysis revealed that although Petrol produced the highest instantaneous energy (1.45 MJ/min), its Relative Efficiency Index (REI) was lowest (0.69). Conversely, CNG achieved the highest REI (1.82), demonstrating superior long-term efficiency. Environmental measurements showed that CNG emitted the lowest pollutants CO (0.9 ppm), NO (0.79 ppm), and NO<sub>2</sub> (0.48 ppm) with no detectable SO<sub>2</sub> or H<sub>2</sub>S. Economically, CNG emerged as the most cost-effective fuel at ₦20.83 per MJ, followed by LPG (₦22.00/MJ) and Petrol (₦27.64/MJ). Overall, CNG stands out as the cleanest, most sustainable, and most economical fuel alternative evaluated.

### 1. INTRODUCTION

The transportation sector plays a vital role in today's global economy, but it also contributes significantly to environmental pollution because it depends heavily on fossil fuels like petrol and diesel (Smith & Taylor, 2023). Burning these fuels releases large amounts of greenhouse gases (GHGs) and harmful pollutants, which worsen air quality, accelerate climate change, and pose risks to public health (Johnson et al., 2022). These growing concerns have pushed many countries to explore cleaner and more sustainable fuel alternatives. Among the options being considered, Liquefied Petroleum Gas (LPG), Natural Gas (NG), and its compressed form, Compressed Natural Gas (CNG), stand out as promising candidates.

LPG made mainly of propane and butane is produced during petroleum refining and natural gas processing. It burns more cleanly than petrol and diesel, resulting in lower emissions of carbon monoxide, nitrogen oxides, and unburned hydrocarbons (Mishra et al., 2023). It also has a high octane rating, which can improve engine performance and prolong engine life (Okoro et al., 2022).

Natural gas, which is mostly methane, is another fuel that has gained global attention. When compressed into CNG, it can be used effectively in internal combustion engines that are designed or converted for gaseous fuels (Sadiq et al., 2023). Vehicles running on CNG tend to emit significantly fewer pollutants, and several studies have reported a 20–29% reduction in carbon dioxide emissions compared to petrol powered vehicles (Johnson & Smith, 2023). CNG's clean combustion also reduces engine wear and lowers maintenance costs, making it attractive from both environmental and economic perspectives (Adebola et al., 2024).

Around the world, the adoption of LPG, NG, and CNG varies widely. Factors such as government policies, public awareness, local fuel availability, and the presence of supporting infrastructure all play important roles. In Nigeria, interest in CNG has increased in recent years especially after the removal of fuel subsidies that caused a sharp rise in petrol prices. Government led conversion and awareness programmes have been introduced to encourage the use of CNG for transportation (Adejumo, 2023; Ibrahim, 2023). However, progress has been slow due to infrastructure gaps, the high cost of vehicle conversion, and limited public understanding of the benefits and safety of these fuels (Eze et al., 2023).

Switching to fuels like LPG and CNG can bring substantial economic and environmental benefits. These include reduced emissions, cleaner air, lower fuel and maintenance costs, and improved energy security through reduced dependence on imported petrol (Ahmed & Bello, 2022; Taylor et al., 2022). However, unlocking these benefits requires addressing challenges related to engine adaptation, storage technology, safety protocols, and the development of accessible refuelling stations (Brown & Davis, 2023; Olawale et al., 2024).

This study therefore provides a comprehensive comparison of LPG, NG, and CNG, focusing on their environmental performance, economic feasibility, infrastructure requirements, and overall suitability as alternative fuels for internal combustion engines. The goal is to support informed decision making and contribute to Nigeria's ongoing transition toward cleaner and more sustainable transportation options.

Despite global efforts to reduce the environmental impact of fossil fuels, petrol and diesel remain the dominant transportation fuels. Their combustion releases large quantities of greenhouse gases, driving climate change, air pollution, and ecological damage (Smith et al., 2023). The transport sector alone contributes roughly 24% of global CO<sub>2</sub> emissions, highlighting the urgent need for cleaner alternatives (IEA, 2022). At the same time, fluctuations in the price of petrol create economic uncertainty especially in developing countries that rely heavily on fuel imports (Adejumo et al., 2023).

Although alternative fuels such as LPG, NG, and CNG offer environmental and economic advantages, their adoption remains limited. Several factors contribute to this slow transition: insufficient refuelling infrastructure, the high cost of converting vehicles, limited public awareness, and persistent doubts about the performance and reliability of vehicles running on these fuels (Eze & Johnson, 2023; Mishra et al., 2023).

In Nigeria, the removal of petrol subsidies has further intensified the need for cheaper, cleaner energy options. The resulting rise in fuel prices has made alternative fuels more attractive to both individuals and businesses (Ibrahim & Ahmed, 2023). However, the lack of strong policy support, inadequate infrastructure investment, and slow implementation of conversion initiatives have hindered widespread adoption of LPG, NG, and CNG (Okoro & Bello, 2024). These challenges clearly show the need for a detailed assessment of alternative fuels to guide the transition to cleaner transportation. This study therefore compares LPG, NG, and CNG in terms of their environmental impact, performance characteristics, cost implications, and infrastructure demands. By identifying their strengths and limitations, the study aims to provide stakeholders policymakers, transport operators, and consumers with the information needed to make informed decisions and support Nigeria's shift toward cleaner, more sustainable fuel options.

## **2. MATERIALS AND METHODS**

### **2.1 Engine Specifications**

A single cylinder, four stroke generator capable of running on LPG, CNG, and Petrol was used. Conversion kits enabled switching between fuels.

### **2.2 Equipment**

- Fuel flow meter
- Stopwatch
- Gas analyzer (for CO, NO, NO<sub>2</sub>, SO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>S)
- Pressurized LPG cylinder
- High pressure CNG cylinder (200–250 bar)

### **2.3 Experimental Procedure**

Calibration of the generator was done to ensure it is in optimal working condition. Installation of the necessary conversion kits for both LPG and CNG usage was carried. 1 kg of each fuel was burned separately in the generator. Ambient temperature and pressure were recorded. Combustion time, emissions, and electricity generated were measured.

### **2.4 Data Analysis**

The burning efficiency of each fuel was calculated based on the time required to burn 1 kg of fuel. Energy efficiency was analyzed by determining the amount of electricity generated per kilogram of fuel. Cost efficiency was evaluated by calculating the cost per kWh of electricity generated using the two fuels. The data was analyzed and presented in comparative tables and graphs for clarity.

- Combustion duration (min/kg)
- Energy rate (MJ/min)
- Relative Efficiency Index (REI)
- Emission concentrations (ppm)
- Cost per megajoule and cost per operating hour

## **3. RESULTS AND DISCUSSION**

### **3.1 Determination of burning rate**

**Table 3.1.** Combustion time for 1kg of fuel

Fuel type	Combustion time			Combustion rate	% Combustion rate
	Start	End	Total		
Petrol (1kg)	9:30am	10:02am	32minutes	0.031	3.125
LPG (1kg)	9:30am	10:55am	75minutes	0.013	1.333
CNG (1kg)	9:30am	11:07am	97minutes	0.010	1.031

Table 3.1 presents the combustion time and rate for 1 kg of petrol, LPG, and CNG when used in an internal combustion engine powered by a generator. Petrol burns completely within 32 minutes, showing the fastest combustion among the three fuels, with a combustion rate of 0.031 and a percentage combustion rate of 3.125%. LPG takes a longer time of 75 minutes to combust, with a lower combustion rate of 0.013 and a percentage rate of 1.333%. CNG has the longest combustion time at 97 minutes, with the slowest combustion rate of 0.010 and the lowest percentage combustion rate of 1.031%. These results indicate that petrol burns faster and is consumed more quickly, while CNG burns slower and lasts longer. Therefore, although petrol offers quicker energy release, CNG provides extended engine run time per kilogram, making it more efficient for prolonged use. This further supports the economic and energy-saving advantage of CNG over petrol and LPG.

### 3.2 Evaluation of energy efficiency of LPG, Petrol (Gasoline) and CNG

**Table 3.2.** Energy efficiency and relative efficiency index of LPG, Petrol (Gasoline) and CNG

Fuel	Calorific Value (MJ/kg)	Time (min)	Energy per minute (MJ/min)	REI (relative units)
Petrol	46.4	32	1.45	0.69
LPG	50.0	75	0.67	1.49
CNG	53.6	97	0.55	1.82

The energy efficiency of a fuel can be assessed by how effectively it delivers energy over time during combustion. As presented in Table 3.2, petrol shows the highest energy per minute (1.45 MJ/min) due to its shorter combustion time, it is also the least efficient overall, as reflected in its lowest REI (0.69). This indicates rapid energy release but lower sustainability over time. On the other hand, Compressed Natural Gas (CNG) has the lowest energy per minute (0.55 MJ/min) but demonstrates the highest relative efficiency index (REI = 1.82). This means CNG burns more slowly and steadily, offering a more prolonged and efficient energy output over time. Its high calorific value (53.6 MJ/kg) and long combustion time (97 minutes) contribute to this performance. Liquefied Petroleum Gas (LPG) sits between Petrol and CNG in terms of energy efficiency. With an energy per minute of 0.67 MJ/min and a REI of 1.49, LPG provides a good balance between energy release rate and efficiency, making it a practical alternative in terms of consistent energy output and fuel economy. These findings are consistent with previous studies that show CNG and LPG offer higher thermal efficiency and better fuel economy than gasoline, particularly in applications requiring sustained operation (Agarwal et al., 2019; Choi & Song, 2020). The lower combustion temperature and cleaner burn of gaseous fuels also result in more efficient engine performance and less energy loss (Okoro & Bello, 2024). Moreover, the slower combustion rate of CNG and LPG reduces thermal stress on

engine components, leading to improved durability and reduced maintenance costs (Kumar et al., 2018). This further enhances their operational efficiency when used in internal combustion engines, especially under consistent load conditions.

### 3.3 Analysis of environmental impact of LPG, Petrol (Gasoline) and CNG

**Table 3.3.** Gas Analyzer Comparison for LPG, Petrol (Gasoline) and CNG

S/N	GAS	LPG	GASOLINE	CNG
1.	O <sub>2</sub>	16.3%	12.4%	12.4%
2.	CO	4.1ppm	2.1ppm	0.9ppm
3.	CO <sub>2</sub>	1.1%	1.1%	1.1%
4.	NO	1.2ppm	1.0ppm	0.79ppm
5.	NO <sub>2</sub>	0.4ppm	0.7ppm	0.48ppm
6.	SO <sub>2</sub>	29.2ppm	0.0ppm	0.0ppm
7.	CH <sub>4</sub>	33.1%	5.7%	21.7%
8.	H <sub>2</sub> S	75.6ppm	0.0ppm	0.0ppm
9.	Pressure	-0.02inwc	-0.02inwc	-0.02inwc

Table 3.3 presents the results of a gas analyzer comparison for LPG, petrol (gasoline), and CNG used in internal combustion engines. The oxygen (O<sub>2</sub>) content is highest in LPG at 16.3%, compared to 12.4% for both petrol and CNG, indicating more excess air in the exhaust of LPG combustion. Carbon monoxide (CO) levels are highest in LPG at 4.1 ppm, lower in petrol at 2.1 ppm, and lowest in CNG at 0.9 ppm, showing that CNG produces the least amount of this toxic gas. Carbon dioxide (CO<sub>2</sub>) levels are the same across all three fuels at 1.1%, suggesting similar combustion efficiency. Nitric oxide (NO) emissions are slightly higher in LPG at 1.2 ppm, compared to 1.0 ppm for petrol and 0.79 ppm for CNG, while nitrogen dioxide (NO<sub>2</sub>) follows a similar pattern, with LPG at 0.4 ppm, petrol at 0.7 ppm, and CNG at 0.48 ppm. Sulfur dioxide (SO<sub>2</sub>) and hydrogen sulfide (H<sub>2</sub>S) are present only in LPG, with values of 29.2 ppm and 75.6 ppm respectively, and are completely absent in both petrol and CNG, indicating the presence of sulfur compounds in LPG. Methane (CH<sub>4</sub>) content is highest in LPG at 33.1%, followed by CNG at 21.7%, and lowest in petrol at 5.7%. The pressure readings are identical across all three fuels at -0.02 inwc. Overall, CNG produces the least harmful emissions (CO, NO, NO<sub>2</sub>, SO<sub>2</sub>, H<sub>2</sub>S) and is therefore the cleanest among the fuels tested, while LPG shows higher pollutant levels, particularly in CO, SO<sub>2</sub>, H<sub>2</sub>S, and CH<sub>4</sub>.

### 3.4 Analysis of economic cost of LPG, Petrol (Gasoline) and CNG

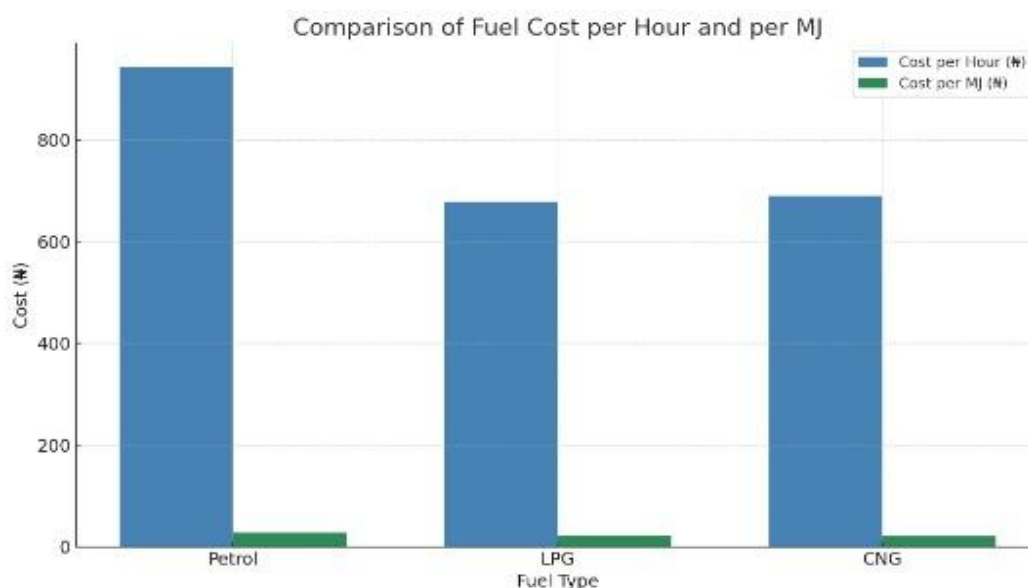


Figure 3.1: Economic cost analysis of various fuels used

Figure 3.1 depicts the economic cost analysis of various fuels used. CNG had the lowest cost per megajoule (₦20.83), making it the most economically efficient fuel. LPG followed with a cost of ₦22.00/MJ, while Petrol was the most expensive at ₦27.64/MJ. Similarly, operational cost per hour was highest for Petrol (₦943.01/hr) and lowest for LPG (₦679.01/hr), with CNG slightly higher at ₦689.66/hr.

## 4. COCLUSIONS AND RECOMMENDATIONS

### 4.1 Conclusions

This study conducted a comparative analysis of Liquefied Petroleum Gas (LPG), Petrol (Gasoline), and Compressed Natural Gas (CNG) as alternative fuels for internal combustion engines. The conclusions drawn from the findings are as follows:

- The combustion time results showed that **Petrol** had the fastest burning rate (32 minutes), followed by **LPG** (75 minutes) and **CNG** (97 minutes). This indicates that Petrol burns more rapidly, but CNG and LPG offer longer combustion durations per kilogram, which may be advantageous for extended engine operations.
- Although **Petrol** delivered the highest energy per minute (1.45 MJ/min), it had the **lowest relative efficiency index (REI)** of 0.69. In contrast, **CNG** and **LPG** had lower energy per minute (0.55 and 0.67 MJ/min, respectively) but demonstrated higher REI values of **1.82 for CNG** and **1.49 for LPG**, indicating superior efficiency in converting fuel energy over longer periods of operation.
- The gas emission analysis revealed that **CNG** produced the lowest levels of harmful emissions such as CO (0.9 ppm), NO (0.79 ppm), and NO<sub>2</sub> (0.48 ppm), making it the cleanest fuel among the three. **Petrol** had moderate emissions, while **LPG** showed higher values for CO (4.1 ppm), SO<sub>2</sub> (29.2 ppm), CH<sub>4</sub> (33.1%), and H<sub>2</sub>S (75.6 ppm), indicating a higher environmental burden.
- In terms of cost-effectiveness, **CNG** was the most economical, with the lowest cost per MJ (₦20.83) and reasonable combustion time. **LPG** followed with a cost of ₦22.00 per MJ, while **Petrol** was the most expensive at ₦27.64 per MJ. Additionally, the cost per hour of

operation was highest for Petrol (₦943.01/hr) compared to LPG (₦679.01/hr) and CNG (₦689.66/hr).

#### **4.2 Recommendations**

1. Government incentives for CNG infrastructure.
2. Expansion of LPG and CNG refueling stations.
3. Public awareness campaigns on safety and economic benefits.
4. Engine optimization for gaseous fuels.
5. Further research on long term engine durability.

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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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## PRODUCTION AND CHARACTERIZATION OF ACTIVATED CARBON FROM COCONUT SHELL: EFFECT OF ACTIVATING AGENTS

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### Abstract

The choice of chemical activating agents plays a vital role in shaping the morphology, porosity, and adsorption efficiency of biomass-derived activated carbon. In this work 1M solution of HCl, H<sub>2</sub>SO<sub>4</sub>, KOH, and NaOH, were used to activate the precursor for 6 hr, followed by carbonization at 500°C for 1 hr and their effects were investigated using morphological analysis, iodine number determination, and FTIR spectroscopy. Surface observations revealed that HCl produced irregular structures with mineral residues and limited porosity, whereas H<sub>2</sub>SO<sub>4</sub> generated compact, layered frameworks that were stable yet less porous. By contrast, KOH produced highly porous structures with well-developed micro- and mesopores, identifying it as the most effective base activator. Iodine analysis indicated that acid-activated carbons exhibited the highest adsorption capacities, with H<sub>2</sub>SO<sub>4</sub> (1795.00 mg/g) and HCl (1793.10 mg/g) outperforming KOH (1730.28 mg/g) and NaOH (1699.83 mg/g). The effectiveness order followed H<sub>2</sub>SO<sub>4</sub> ≈ HCl > KOH > NaOH, underscoring the stronger adsorption potential of acid treatments. In other word, H<sub>2</sub>SO<sub>4</sub> promotes dehydration, sulfonation, and mesopore formation, while HCl primarily enhances porosity by leaching minerals. FTIR spectra supported these differences: KOH and NaOH exhibited similar oxygenated groups (C–O, O–H, aromatic C=C), H<sub>2</sub>SO<sub>4</sub> introduced additional sulphate functionalities alongside stronger O–H and C=O peaks, and HCl increased acidic oxygen groups without sulfonation. In conclusion, KOH is effective for micropore development, but acid activators (H<sub>2</sub>SO<sub>4</sub>, HCl) deliver superior adsorption capacity through enhanced surface chemistry. These findings emphasize the need to tailor activating agents to the intended application by balancing pore structure and surface functionality.

### 1.0 INTRODUCTION

Activated carbon is a widely used adsorbent in water purification, gas separation, catalysis, and environmental remediation, owing to its high surface area, well-developed porosity, and abundance of surface functional groups. Its performance depends largely on the precursor material and activation method. Among biomass precursors, coconut shell is particularly

attractive due to its high lignin and carbon content, low ash content, mechanical strength, and availability in tropical regions (Chew et al., 2023; Baharum et al., 2020).

The production of activated carbon typically involves carbonization to remove volatile matter, followed by activation to develop porosity and surface chemistry. Activation may be achieved by physical means (e.g., steam or CO<sub>2</sub> at high temperature) or chemical methods (using acids, bases, or salts). Chemical activation is generally more effective, as it facilitates pore development at lower temperatures while simultaneously introducing surface functional groups (Chew et al., 2023; Ademiluyi and David-West., 2012).

The choice of activating agent significantly influences the final properties of activated carbon. Alkaline activators such as potassium hydroxide (KOH) and sodium hydroxide (NaOH) intercalate into the carbon matrix, promoting micropore formation through redox and etching reactions. KOH is particularly effective, often producing sponge-like carbons with exceptionally high surface areas, while NaOH yields similar but less pronounced effects (Samghouli *et al.*, 2025). In contrast, acidic activators such as hydrochloric acid (HCl) and sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) act mainly through demineralization and oxidation. HCl removes residual minerals and enlarges existing pores, whereas H<sub>2</sub>SO<sub>4</sub> promotes dehydration and sulfonation, producing more stable structures enriched with acidic groups (S=O, carbonyl, carboxyl), which enhance polarity and adsorption of polar contaminants (Samghouli et al., 2025; Seo-Hyun Pak, 2016).

To evaluate these effects, a range of characterization techniques are employed, including scanning electron microscopy (SEM) for morphological analysis, iodine number or BET surface area measurements for adsorption capacity, Fourier-transform infrared spectroscopy (FTIR) for surface functional groups, and proximate/ultimate analysis for elemental composition and thermal stability.

By comparing different activating agents, researchers can tailor pore structure and surface chemistry to specific applications. While KOH remains the most effective for developing microporous carbons suited for gas adsorption, acid activators such as H<sub>2</sub>SO<sub>4</sub> and HCl are advantageous in applications requiring enhanced surface acidity and polarity, including catalysis and wastewater treatment. Therefore, this study investigates the production and characterization of coconut-shell-derived activated carbon using HCl, H<sub>2</sub>SO<sub>4</sub>, KOH, and NaOH, with emphasis on their effects on morphology, porosity, surface chemistry, and adsorption performance.

## **2.0 MATERIALS AND METHODS**

Coconut Shell, Beaker, Crusher and milling machine, Oven, Muffle Furnace, Sieve (0.28 mm), pH Meter, Glassware, Weighing Balance, Stop watch, Filter paper, Hydrochloric Acid (HCl), Sulphuric Acid (H<sub>2</sub>SO<sub>4</sub>), Potassium hydroxide (KOH), Sodium hydroxide (NaOH), distilled water.

### **2.1 Raw Materials Collection and Treatment:**

Coconut shells were collected from local markets and roadside vendors in Bakin Dogo Market, Kaduna State, chosen for their availability, low cost, and high carbon content. The shells were manually broken to remove residual pulp and fibers, then thoroughly washed with clean tap water followed by distilled water to eliminate dirt, dust, and soluble impurities. The cleaned shells were sun-dried for 2-3 days and then oven-dried at 120°C for 1 hour to ensure complete removal of moisture. The dried shells were stored in airtight containers prior to particle size reduction and carbonization to prevent reabsorption of atmospheric moisture.

## **2.2 Crushing/Grinding Process:**

The cooled coconut shell was subjected to mechanical size reduction to enhance its surface area and facilitate uniform chemical activation. The charred material was first manually broken into smaller fragments, then transferred to a high-speed mechanical grinder for fine grinding. The grinding process was carefully controlled to avoid excessive heat generation, which could alter the material's microstructure. The ground material was subsequently sieved using a standard mesh (0.28 mm) to obtain a uniform particle size distribution suitable for carbonization and activation. This size uniformity is essential to ensure consistent pore development during the activation process and to enhance adsorption efficiency during wastewater treatment.

## **2.3 Carbonization and Activation Process:**

The coconut shell powder was treated with 1M solution of different activating agent (HCl, H<sub>2</sub>SO<sub>4</sub>, NaOH and KOH) for 6 hour at room temperature. The paste was washed with distilled water to a neutral pH, followed by oven drying overnight at 120<sup>0</sup>C. The oven dried samples were subjected to carbonization in a muffle furnace under limited oxygen conditions at temperature of 500<sup>0</sup>C for 1 hour. This process facilitated the removal of volatile organic compounds and the formation of a rigid carbon skeleton. The resulting coconut shell activated carbon was allowed to cool in a desiccator to avoid moisture uptake and was then ground using a mechanical grinder. The ground material was sieved using a standard mesh (0.28 mm) and stored in air-tight labeled sample bottle for characterization.

## **2.4 Characterization of Produced Activated Carbon:**

### **1. Scanning Electron Microscopy (SEM) Analysis**

The morphological structure of the coconut shell activated carbon was examined using SEM (PhenomWorld Pro X). This technique provided visual evidence of the porosity and surface roughness, which are critical for adsorption.

### **2. Fourier Transform Infrared (FTIR) Spectroscopy:**

FTIR spectrophotometer (Shimadzu 8400s) was used to identify the functional groups present on the surface of the activated carbon. Samples were prepared using the KBr pellet method and analyzed within the wavenumber range of 4000–400 cm<sup>-1</sup>. The spectra obtained were interpreted to determine the presence of key functional groups such as hydroxyl (–OH), carbonyl (C=O), and carboxylic (–COOH) groups, which are responsible for adsorption. This analysis provided insight into the surface chemistry and potential adsorption mechanisms of the activated carbon derived from coconut shell.

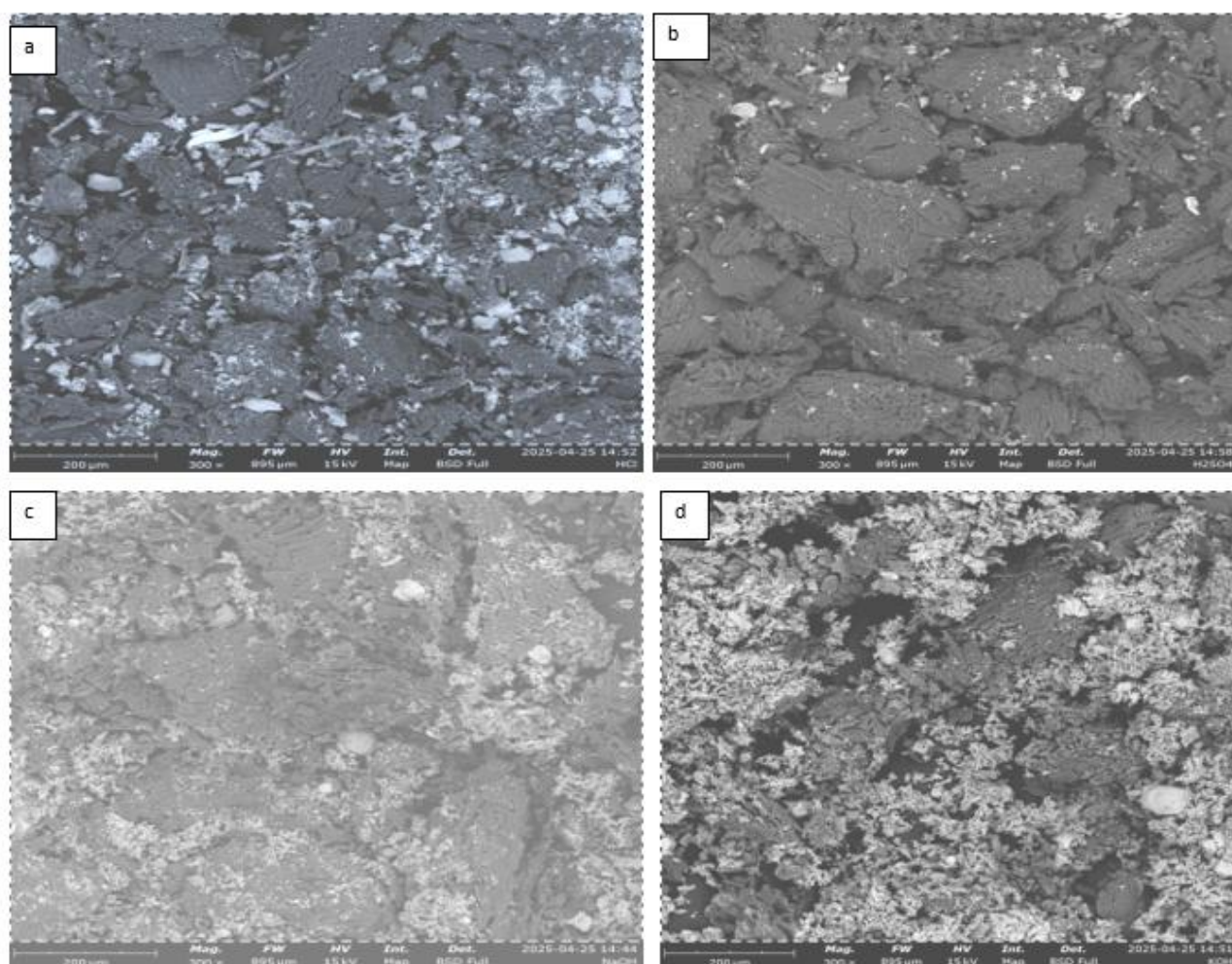
### **3. Iodine value**

Iodine value (IV) of each sample was determined by the titration of 0.1 M Sodium thiosulphate solution against 60.0 ml of the sample free liquor solution (prepared 0.5 g of each samples in 75.0 ml of 0.086 M iodine solution using starch indicator. The iodine value (IV) was calculated using the formula:  $IV (mg/g) = (Y - X) * V * M * 12.69 / W$  Where Y = volume of thiosulphate for blank, X = Titer value, V = volume iodine solution used, W= Weight of sample. M = molarity of Sodium thiosulphate solution.

### 3.0 RESULTS AND DISCUSSION

#### 3.1 SEM analysis

The morphological structure of the prepared activated carbon using HCl, H<sub>2</sub>SO<sub>4</sub>, NaOH and KOH as activating agents, is presented in figure 4a-d, respectively. SEM analysis revealed clear differences in morphology depending on the activating agent. HCl-treated carbon showed heterogeneous surfaces with residual minerals and limited pore formation, while H<sub>2</sub>SO<sub>4</sub>-treated carbon produced compact, layered structures with low porosity but high surface functionality. In contrast, NaOH-treated carbon exhibited moderate porosity with shallow, less connected pores, whereas KOH-treated carbon developed highly porous, sponge-like morphologies with micropore and mesopore networks. These morphological trends were consistent with iodine adsorption capacities: H<sub>2</sub>SO<sub>4</sub> (1795.00 mg/g) and HCl (1793.10 mg/g) gave the highest values, reflecting their strong influence on surface functionalization. KOH (1730.28 mg/g) outperformed NaOH (1699.83 mg/g) in pore generation, though both bases showed lower iodine values than the acids. FTIR confirmed these distinctions, with acids introducing stronger O–H and C=O functionalities (and sulphate groups in H<sub>2</sub>SO<sub>4</sub>), while alkalis primarily generated carboxyl and phenolic groups associated with microporosity.



**Figure 1.** SEM Analysis of activated carbon using: a) HCl b) H<sub>2</sub>SO<sub>4</sub> c) NaOH d) KOH

#### 3.2 Iodine value analysis

The iodine values of the samples ranged between 1699.83 and 1795.00 mg/g as presented in Table 1. The highest adsorption capacity was obtained with H<sub>2</sub>SO<sub>4</sub> (1795.00 mg/g), closely

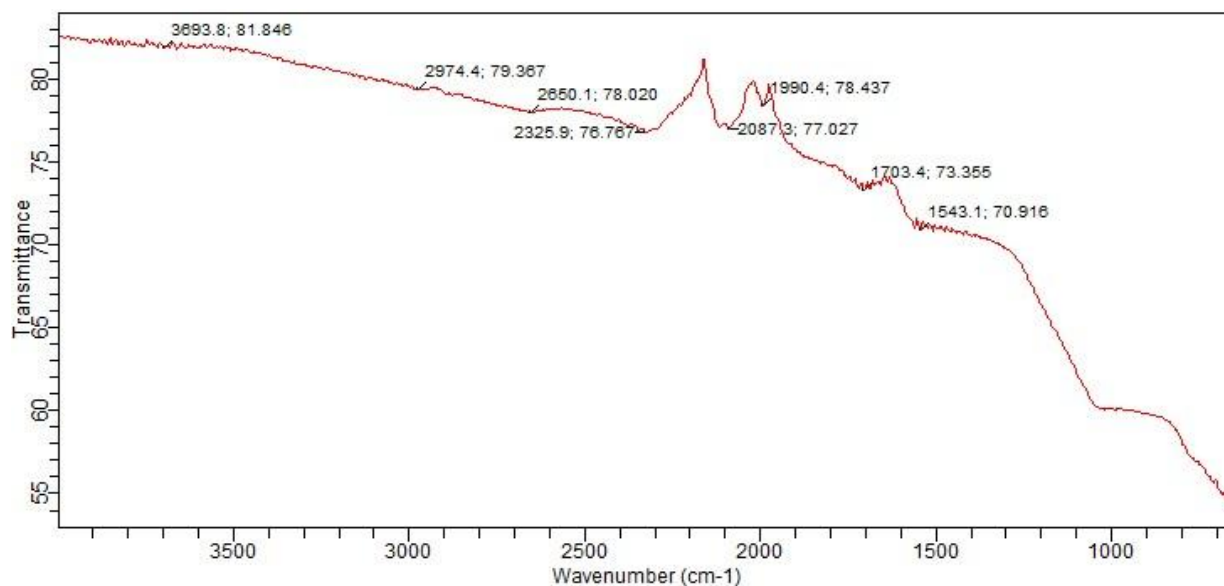
followed by HCl (1793.10 mg/g). NaOH (1699.83 mg/g) showed the lowest value, indicating the weakest activation effect. KOH (1730.28 mg/g) performed better than NaOH but was less effective than the acids. In general, acid-activated carbons (H<sub>2</sub>SO<sub>4</sub> and HCl) demonstrated greater adsorption potential compared to base-activated carbons (NaOH and KOH). H<sub>2</sub>SO<sub>4</sub> and HCl showed nearly the same level of performance. The overall order of effectiveness was: H<sub>2</sub>SO<sub>4</sub> ≈ HCl > KOH > NaOH. Studies indicate that while H<sub>2</sub>SO<sub>4</sub> and HCl can both serve as effective acid activators, their mechanisms differ: H<sub>2</sub>SO<sub>4</sub> typically promotes dehydration/sulfonation and mesopore formation, whereas HCl primarily leaches minerals and enlarges pores (Chew et. al., 2023). Regarding bases, Research has shown that KOH outperforms NaOH in producing activated carbon with higher microporosity, BET surface area, and adsorption capacity (Togibasa et. al., 2021).

**Table 1: IODINE VALUE DATA FOR FOUR CARBONIZED SAMPLES**

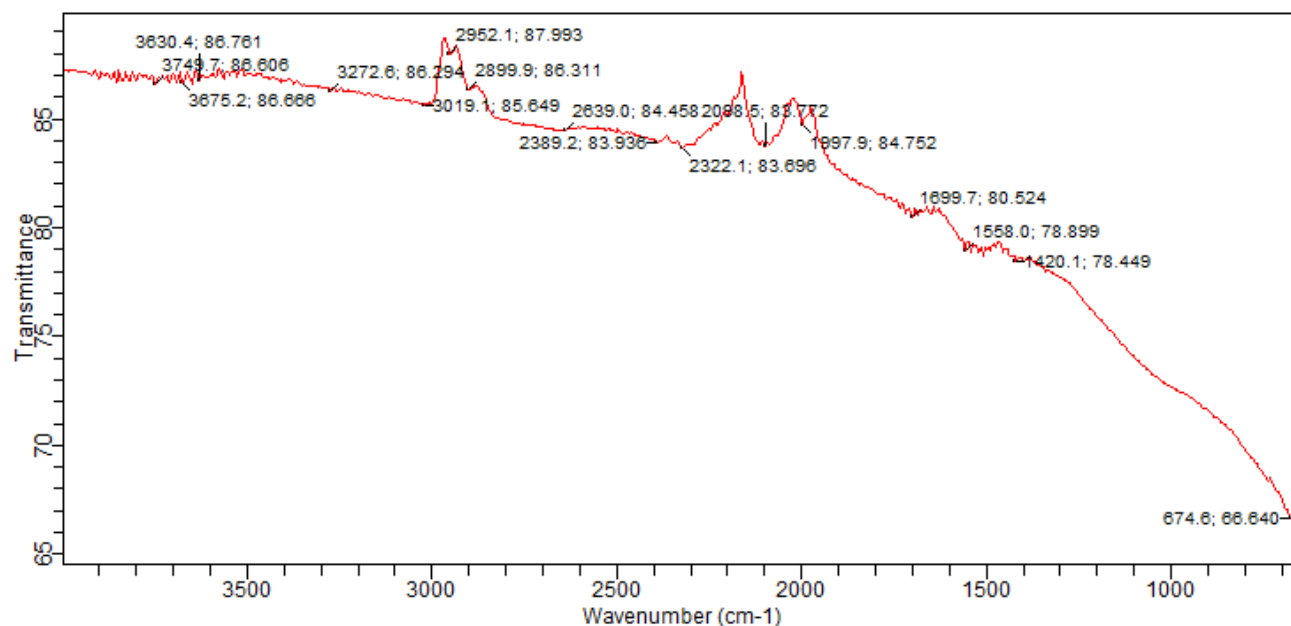
S/N	SAMPLE ID	Blank Y (ml)	Sample X (ml)	Vol. Iodine (ml)	Thios. Conc. (Mol)	Const.	Mass (g)	Iodine Value IV = (y-x)*Vol.*Conc.*Const./Mass
1	NaOH	9.6	0.67	75	0.1	12.69	0.5	1699.8255
2	H <sub>2</sub> SO <sub>4</sub>	9.6	0.17	75	0.1	12.69	0.5	1795.0005
3	KOH	9.6	0.51	75	0.1	12.69	0.5	1730.2815
4	HCl	9.6	0.18	75	0.1	12.69	0.5	1793.097

### 3.3 FTIR Spectral Analysis of Activated Carbon

The presence of various functional groups on the surface of the samples was analysed using Fourier Transform Infrared (FTIR) spectrometer (Shimadzu 8400s) and the IR spectra of the activated carbon prepared from coconut shell using HCl, H<sub>2</sub>SO<sub>4</sub>, NaOH and KOH as activators are shown in figures 3, 4, 5 and 6, respectively. The resulting spectra revealed distinct functional group profiles, each reflecting the chemical influence of the activating agent on the carbon's surface properties. Activated carbon treated with HCl displayed peaks associated with hydroxyl (O–H) (3693.3 cm<sup>-1</sup>) and aliphatic (C–H) (2974.8, 2850.6 cm<sup>-1</sup>) groups, as well as carbonyl or aromatic (C=O/C=C) (1643.1 cm<sup>-1</sup>) functionalities. These groups contribute to adsorption via hydrogen bonding and π–π interactions (Kumar et al., 2023). In comparison, H<sub>2</sub>SO<sub>4</sub>-treated carbon exhibited more intense O–H bands (3630.4–3749.7 cm<sup>-1</sup>), along with sulfate-related S=O vibrations (1420.1 cm<sup>-1</sup>) and out-of-plane aromatic bending mode (674.6 cm<sup>-1</sup>), similar to what was reported by Ali et. al., 2020. The presence of these oxygen-rich groups enhances hydrophilicity and electrostatic attraction, particularly for organic pollutants, like cationic dye (Shojaei & Esmaili, 2022). NaOH activation resulted in strong O–H (3049 cm<sup>-1</sup>) and C–H (2881.2 cm<sup>-1</sup>) stretching, along with carbonyl (C=O) (2642.70 cm<sup>-1</sup>), and carboxyl-related (C–O) (1423.8 cm<sup>-1</sup>) vibrations. These functionalities are known to facilitate adsorption through ion exchange and surface complexation (Kazempour & Bagheri-Mohagheghi, 2023). KOH-treated carbon showed similar C–H stretching (3000.6 cm<sup>-1</sup>), with additional bands suggesting triple bond vibrations, and prominent C–O (1114.5 cm<sup>-1</sup>) and N–H (868.7 cm<sup>-1</sup>) features, which indicates a highly porous structure with basic surface sites. The variation in functional group intensity and diversity across samples directly affects their adsorption behaviour. Acid treatments tend to introduce more polar and oxygenated groups while base treatments favour carboxyl and phenolic groups (Shojaei & Esmaili, 2022; Zhao et al., 2022). FTIR Peak Assignments of Activated Carbon Prepared with Different Activating Agents are presented in Table 2.



**Figure 2.** FTIR analysis using activated carbon prepared using HCl

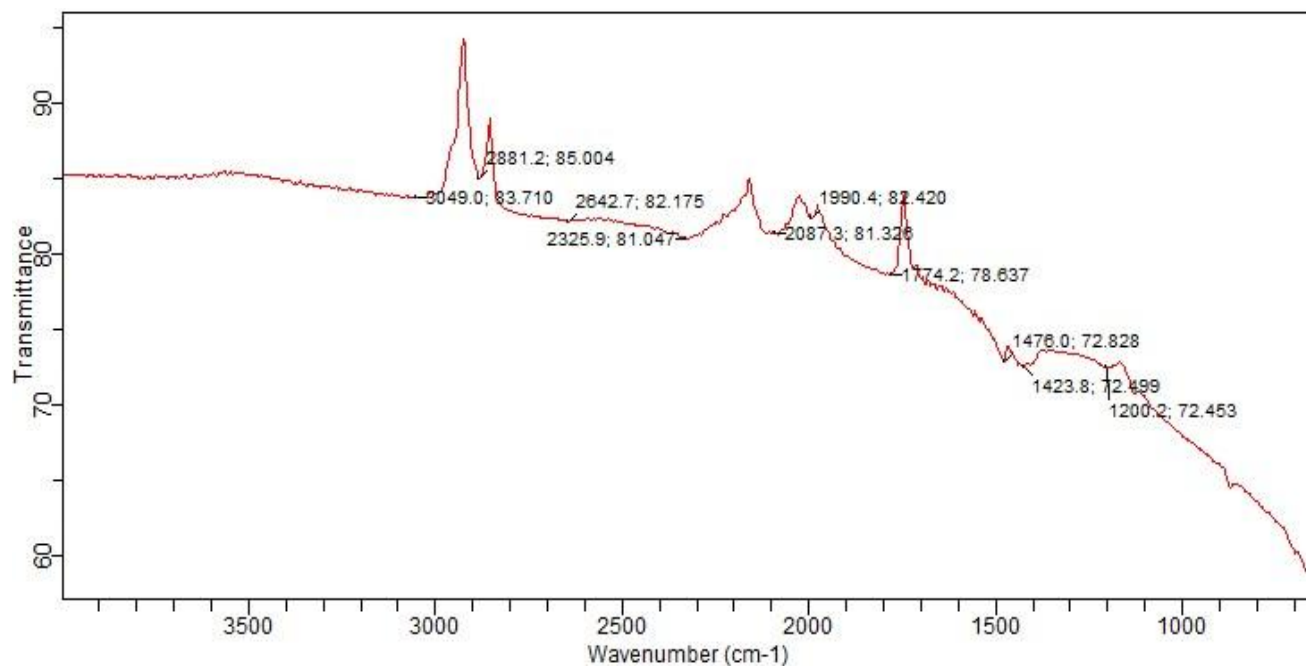


**Figure 4.2.** FTIR analysis using activated carbon prepared using H<sub>2</sub>SO<sub>4</sub>

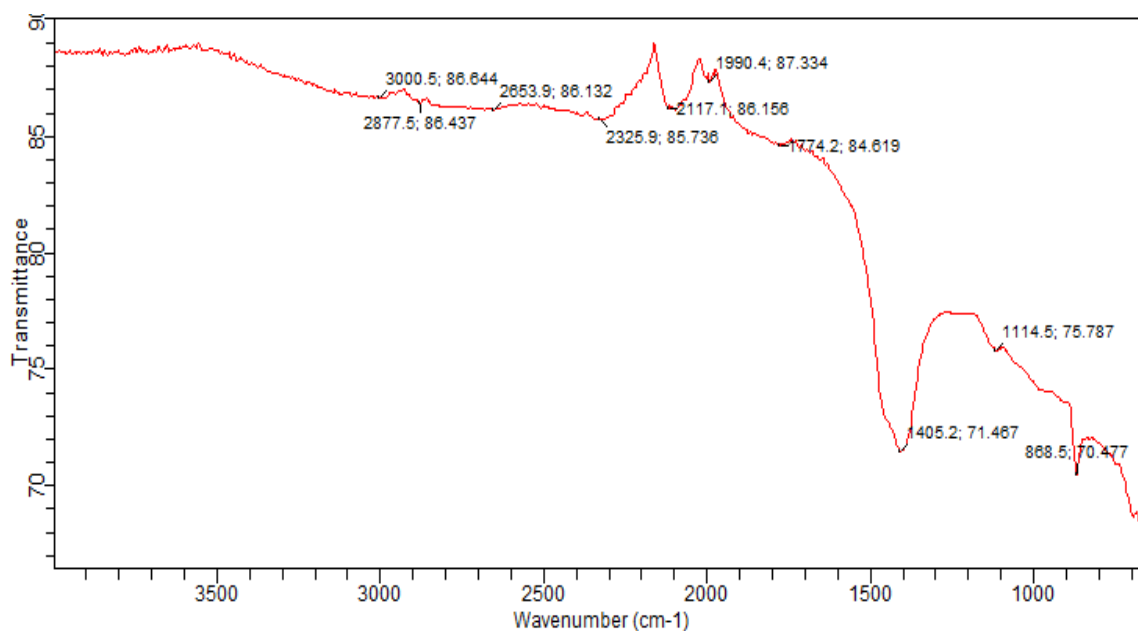
#### **4.0 CONCLUSIONS AND RECOMMENDATIONS**

Activated carbon has been successfully prepared from coconut shell using HCl, H<sub>2</sub>SO<sub>4</sub>, NaOH and KOH as the activating agents. Surface analysis was done using SEM and FTIR spectroscopy, while the adsorption capacity was tested with iodine value analysis. Acid-activated carbons (H<sub>2</sub>SO<sub>4</sub>, HCl) showed the highest iodine values (1795 and 1793 mg/g), outperforming alkali-activated carbons (KOH: 1730 mg/g; NaOH: 1700 mg/g). H<sub>2</sub>SO<sub>4</sub> promoted sulfonation and surface acidity, while HCl mainly enhanced oxygenation via demineralization. KOH produced the most porous sponge-like structure, ideal for micro porosity, whereas NaOH was the least effective. FTIR confirmed KOH and NaOH exhibited similar groups (C–O, O–H, aromatic C=C), H<sub>2</sub>SO<sub>4</sub> introduced additional sulphate

functionalities alongside stronger O–H and C=O peaks, and HCl increased acidic oxygen groups without sulfonation, while bases favoured C–O functionalities. In conclusion, KOH is effective for micropore development, but acid activators (H<sub>2</sub>SO<sub>4</sub>, HCl) deliver superior adsorption capacity through enhanced surface chemistry. These findings emphasize the need to tailor activating agents to the intended application by balancing pore structure and surface functionality. The presence of functional groups such as hydroxyl, carboxyl, and aromatic groups enhances the material's performance in environmental applications.



**Figure 3.** FTIR analysis using activated carbon prepared using NaOH



**Figure 4.** FTIR analysis using activated carbon prepared using KOH

**Table 2. FTIR Peak Assignments of Activated Carbon Prepared with Different Activating Agents**

Activating Agent	Wavenumber (cm <sup>-1</sup> )	Functional Group	Vibrational Mode	Reference
HCl	3693.3	O–H (hydroxyl)	Stretching	(Kumar et al., 2023)
	2974.8, 2850.6	C–H (alkyl)	Stretching	(Kumar et al., 2023)
	1643.1	C=O / C=C (carbonyl/aromatic)	Stretching	(Kumar et al., 2023)
H <sub>2</sub> SO <sub>4</sub>	3630.4–3749.7	O–H (hydroxyl)	Stretching	(Shojaei & Esmaeili, 2022)
	2952.1, 2899.9	C–H (alkyl)	Stretching	(Shojaei & Esmaeili, 2022)
	1699.7	C=O (carbonyl)	Stretching	(Shojaei & Esmaeili, 2022)
	1420.1	S=O (sulfate)	Stretching	(Shojaei & Esmaeili, 2022)
	674.6	Aromatic C–H	Out-of-plane bending	(Shojaei & Esmaeili, 2022)
NaOH	3049	O–H (hydroxyl)	Stretching	(Kazempour & Bagheri-Mohagheghi, 2023)
	2881.2	C–H (alkyl)	Stretching	(Kazempour & Bagheri-Mohagheghi, 2023)
	2642.7	C=O (carbonyl)	Stretching	(Kazempour & Bagheri-Mohagheghi, 2023)
	1423.8	C–O (phenolic/carboxylic)	Bending/Stretching	(Kazempour & Bagheri-Mohagheghi, 2023)
KOH	3000.6	C–H (alkyl)	Stretching	(Singh et al., 2021)
	1990.4	C≡C	Stretching	(Singh et al., 2021)
	1114.5	C–O (ether/phenolic)	Stretching	(Singh et al., 2021)
	868.7	N–H	Stretching	(Singh et al., 2021)

#### 4.1 Recommendations

H<sub>2</sub>SO<sub>4</sub> and HCl are best for water treatment (polar contaminants), while KOH is ideal for gas adsorption and energy storage. Future work should optimize activation conditions, explore acid–alkali sequential methods, and apply other characterization techniques for deeper characterization.

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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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# OPTIMAL DESIGN OF HYBRID PHOTOVOLTAIC-DIESEL-BATTERY POWER SYSTEM MODEL FOR RURAL ELECTRIFICATION USING WHALE OPTIMIZATION ALGORITHM

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## Abstract

The electrification of remote rural areas remains a significant challenge in developing nations like Nigeria, where grid extension is often economically unviable. Hybrid renewable energy systems (HRES) present a sustainable solution, but their effectiveness hinges on optimal component sizing to balance cost and reliability. This study proposes a novel application of the Whale Optimization Algorithm (WOA) for the optimal design of a standalone hybrid PV-Diesel-Battery system for Agbokeke, rural community of Oyo State Nigeria. The multi-objective optimization model aims to minimize the Total Annualized Cost (TAC) and Total Annual Pollution (TAP). System components are modeled in MATLAB/Simulink, and the load and solar resource data are based on field surveys and national databases. The WOA-derived optimal configuration is compared against two baseline scenarios (Diesel-only and PV-Battery-only) and a standard tool (HOMER Pro). Results show that the WOA-optimized system (73 PV panels, 69 batteries, 50 kVA DG) achieved a TAC of ₦19,546,453 and a TAP of 35.73 Mg of CO<sub>2</sub>, outperforming the HOMER Pro solution by 11.34% in cost and 9.8% in emissions reduction. The findings demonstrate that WOA is a superior, efficient tool for the techno-economic optimization of HRES, providing a viable pathway for cost-effective and environmentally friendly rural electrification.

## 1. INTRODUCTION

In recent times, the continuous availability of electrical energy has offered vital roles for a comfortable life in both rural and urban settlements. Electrical Energy is essential and one of the most critical amenities in our everyday life which help drives some sectors such as healthcare, education, entertainment and transportation in the world of technological development. However, according to the statistics from the International Energy Agency

(IEA), more than 1.5 billion people, representing 14 % of the world's population have zero access to energy as of 2020. Moreover, the larger percentage of this population is located in developing countries, especially in south Asia and the sub-Saharan Africa. One of such country is Nigeria, the most populous black nation located in the south-east of West Africa (Oladigbolu et al., 2020).

Despite its status as one of the fastest growing Africa countries, the country still shows discrepancy in the electrification rate between rural and urban areas. In rural areas, extending the power grid is often a challenging task due to various factors such as rugged terrain, dense jungles, geographic remoteness, high supply costs, low electricity consumption, inadequate road infrastructure, and dispersed settlements of consumers. Hybrid energy systems are best suited to reduce dependence on fossil fuel using available wind speed and solar radiation. As a result, many people in remote areas may need to rely on other sources of power, such as diesel or petrol generators, to meet their electricity needs. There are drawbacks of noise pollution, green-house gas emission, and still very much requires the frequent maintenance cost of fuelling and oiling (Oladigbolu et al., 2020; Diab et al., 2019).

The design of hybrid power system has been attempted by some researchers using simulation software tools. However, the evaluation of the software's limitations, climatic condition of the location and type of system configurations has limited the outcome of expected results (Mostafa et al., 2018). Therefore an optimisation techniques help eliminate some of this limitation (Bhandari et al., 2014; Mostafa et al., 2018). Therefore, in this study, the optimisation algorithm namely Whale Optimisation Algorithm (WOA) was used to optimally design a hybrid PV-diesel-battery power system model for a remote location in western part of Nigeria.

## **2.1 Problem Statement**

The persistent energy deficit in rural areas of developing nations, particularly in sub-Saharan Africa, represents a critical barrier to socio-economic development. In Nigeria, despite having a national installed grid capacity of over 13,000 MW, actual generation often falls below 5,000 MW, leaving millions of people, especially in remote villages, without reliable electricity (Esan, 2019). Extending the central grid to these areas is frequently economically prohibitive due to factors such as difficult terrain, low population density, and high transmission losses (Oladigbolu et al., 2020). Consequently, communities like Agbokeke village in Oyo State, Nigeria, often resort to standalone diesel generators. However, this solution is plagued by exorbitant operational costs due to volatile fossil fuel prices, significant greenhouse gas emissions contributing to environmental pollution, and high maintenance requirements (Ali et al., 2019; Diab et al., 2019).

Renewable energy sources, particularly solar photovoltaic (PV) systems, offer a clean and abundant alternative, harnessing Nigeria's substantial solar potential of approximately 5.12 kWh/m<sup>2</sup>/day on average (Sambo, 2008). Nevertheless, the inherent intermittency and stochastic nature of solar radiation threaten the reliability of a standalone PV system, often necessitating massive battery storage banks to ensure uninterrupted power supply. This requirement for oversizing leads to substantial initial capital investment, making a PV-battery-only system financially unviable for many rural applications (Bhandari et al., 2014; Garcia et al., 2017). Therefore, the specific research problem addressed in this study is the lack of an efficient and robust optimization framework for determining the techno-economically optimal configuration of a standalone PV-Diesel-Battery hybrid system that minimizes total cost and environmental impact for rural electrification in Nigeria. This study investigates whether the

Whale Optimization Algorithm can effectively solve this multi-objective design problem and deliver a superior configuration compared to conventional methods like HOMER.

## 2. MATERIALS AND METHODS

### 2.1. Case Study and Input Data

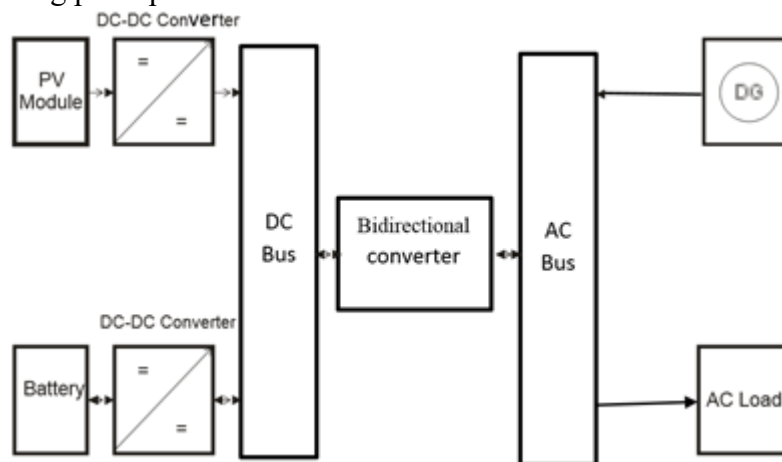
The study focuses on Agbokeke village (8° 41.2' N, 3° 37.3' E) in Oyo State, Nigeria. The village, with an estimated 750 households, has no grid access. The average daily solar radiation is 5.12 kWh/m<sup>2</sup>/day, with a average temperature of 23.29°C (Table 1). The load profile was determined through surveys, showing a peak demand of 35 kW and daily energy consumption ranging from 304 kWh (rainy season) to 415 kWh (dry season).

**Table 1.** Monthly Solar Resource and Climatic Data for Agbokeke, Nigeria

S/N	Months	Average Ambient Temperature (°C)	Average Solar Irradiance (kWh/m <sup>2</sup> /day)	Average Clearness Index
1	January	24.570	5.630	0.622
2	February	26.670	5.870	0.606
3	March	27.550	6.020	0.585
4	April	27.240	5.730	0.546
5	May	26.280	5.430	0.525
6	June	25.130	4.780	0.471
7	July	24.130	4.120	0.404
8	August	23.830	3.830	0.370
9	September	24.270	4.220	0.410
10	October	24.860	4.760	0.485
11	November	24.910	5.380	0.587
12	December	24.140	5.560	0.631
Annual Average		5.12	25.05	0.520

### 2.2. System Architecture and Component Modeling

The proposed HRES comprises PV panels, a diesel generator (DG), a battery bank, and a bi-directional converter (Figure 1). The mathematical models for each component are based on standard energy engineering principles.



**Figure 1.** Block Diagram of the Off-Grid standalone PV-Diesel-Battery hybrid system

1. **PV Array Model:** The hourly output power of the PV array,  $P_{PV}(t)$ , is calculated as:  

$$P_{PV}(t) = N_{PV} \times P_{rated,PV} \times (G(t)/G_{STC}) \times [1 - \alpha (T_c(t) - T_{STC})]$$
 where  $N_{PV}$  is the number of panels,  $P_{rated,PV}$  is rated power under standard test conditions (STC),  $G(t)$  is solar irradiance,  $G_{STC}$  is irradiance at STC,  $\alpha$  is the temperature coefficient, and  $T_c(t)$  is the cell temperature.
2. **Diesel Generator Model:** The fuel consumption of the DG,  $F(t)$ , is modeled using a linear fuel curve:
3.  $F(t) = F_0 \times P_{rated,DG} + F_1 \times P_{DG}(t)$
4. where  $F_0$  and  $F_1$  are fuel curve coefficients, and  $P_{DG}(t)$  is the generator's output power.
5. **Battery Bank Model:** The State of Charge (SOC) of the battery bank is dynamically modeled as:
6.  $SOC(t) = SOC(t-1) \times (1 - \sigma) + (P_{ch}(t) \times \eta_{ch} - P_{dis}(t) / \eta_{dis}) \times \Delta t / C_{rated}$

Where  $\sigma$  is the self-discharge rate,  $P_{ch}$  and  $P_{dis}$  are charging/discharging power,  $\eta_{ch}$  and  $\eta_{dis}$  are efficiencies, and  $C_{rated}$  is the nominal battery capacity.

## 2.3. Problem Formulation

### 2.3.1. Objective Functions

A multi-objective function is formulated to minimize both the Total Annualized Cost (TAC) and Total Annual Pollution (TAP).

$$\text{Min } F = w_1 \times \text{TAC} + w_2 \times \text{TAP}$$

Where  $w_1$  and  $w_2$  are weighting factors ( $w_1 + w_2 = 1$ ), set to 0.7 and 0.3 respectively to prioritize cost while considering emissions. The TAC includes initial capital cost (CC), replacement cost (RC), operation and maintenance cost (O&M), fuel cost, and salvage value (SV) over the project's 25-year lifespan, annualized using a 5% interest rate.

The TAP is calculated from the DG's emissions based on its fuel consumption.

### 2.3.2. Decision Variables and Constraints

The decision variables optimized by the WOA are:

- $N_{PV}$ : Number of PV panels
- $N_{Bat}$ : Number of batteries
- $P_{DG}$ : Capacity of the diesel generator (kW)

The optimization is subject to the following constraints:

- Power Balance:  $P_{PV}(t) + P_{DG}(t) \pm P_{Bat}(t) = P_{Load}(t)$
- Battery SOC:  $SOC_{min} \leq SOC(t) \leq SOC_{max}$
- DG Operating Limit:  $P_{DG,min} \leq P_{DG}(t) \leq P_{DG, rated}$

## 2.4. Whale Optimization Algorithm (WOA) Implementation

The WOA mimics the hunting behavior of humpback whales, which involves encircling prey, bubble-net attacking (exploitation), and searching for prey (exploration). Each "whale" in the population represents a potential system configuration ( $N_{PV}$ ,  $N_{Bat}$ ,  $P_{DG}$ ). The algorithm proceeds as follows:

1. *Initialization:* A population of whales (candidate solutions) is randomly initialized.

2. *Fitness Evaluation*: Each solution is evaluated by simulating the HRES over one year (8760 hours) and calculating the objective function F.
3. *Update Positions*: The positions of the whales are updated based on the WOA's equations for encircling, spiral bubble-net feeding, or random search.
4. *Termination*: Steps 2-3 repeat until a maximum number of iterations is reached (set to 500 in this study).
5. The best solution found represents the optimal system configuration.

### 3. RESULTS AND DISCUSSION

#### 3.1. Optimal Configuration and Comparative Analysis

Three scenarios were analyzed to evaluate the proposed system's performance:

- Scenario 1: Diesel Generator only.
- Scenario 2: PV-Battery only.
- Scenario 3: WOA-Optimized PV-Diesel-Battery system.

The results are summarized in Table 2. The Diesel-only system has the lowest capital cost but the highest TAC due to exorbitant fuel expenses and the highest TAP. The PV-Battery system produces zero emissions but has the highest TAC due to the massive over-sizing required to ensure reliability during low-sunlight periods. The WOA-optimized hybrid system strikes an optimal balance, achieving the lowest TAC and a significantly reduced TAP.

**Table 2.** Performance Comparison of Different System Configurations

Description	Configuration	Total Annual Cost (TAC)	Total Annual Pollution (TAP)
Scenario One (DG Only)	50KVA	₦41,754,160	234.85 Mg
Scenario Two (PV-Battery)	210 PV; 210 BATT.	₦51,450,000	0.00 Mg
Scenario Three: WOA-Optimized	50KVA DG, 73 PV, 69 BATT.	₦19,546,453	35.73 Mg

#### 6.2. Validation against HOMER Pro

The WOA-optimized configuration was compared with a design from HOMER Pro software. HOMER suggested a configuration with 79 PV panels and 72 batteries. The comparative results (Table 3) demonstrate the superior performance of the WOA, yielding an 11.34% reduction in TAC and a 9.8% reduction in TAP.

**Table 3.** Comparison of Optimal system configuration with HOMER software

Serial Number	Metric	HOMER Pro	Optimal System Configuration using WOA	% Improvement by WOA
1	Number of PV Panels	79	73	-
2	Number of Batteries	72	69	-
3	TAC (₦)	22,047,000	19,546,453	11.34%
4	TAP (Mg of CO <sub>2</sub> )	39.62	35.73	9.80%

This superior performance is attributed to WOA's effective global search capability, which allows it to escape local optima and find a more efficient balance between component sizes and operational strategy, thereby minimizing fuel consumption and associated costs more effectively than HOMER's iterative search method.

#### **4. CONCLUSION**

This study successfully demonstrated the application of the Whale Optimization Algorithm for the optimal design of a hybrid PV-Diesel-Battery system for rural electrification. The results of the optimal system configuration were compared with those of HOMER software, the TAC and TAP obtained using HOMER are ₦22,047,000 and 39.62; as compared with ₦19,546,453 and 35.73 Mg respectively, which is about 11.34 % and 9.8 % savings achieved with optimal system configuration using WOA. The WOA proved to be a highly effective tool, outperforming standard software (HOMER Pro) by significantly reducing both the total annual cost and environmental impact. The optimized system configuration provides a reliable, cost-effective, and cleaner energy solution for the remote community of Agbokeke.

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#### **Conflicts of Interest**

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- Suresh, V., & Meenakumari, R. (2021). A review on metaheuristic algorithms for optimal integration of renewable energy sources



## STRENGTH CHARACTERISTICS OF FILTER MEDIA THICKNESS ON ELECTROKINETICALLY REMEDIATED LEAD- CONTAMINATED SOIL

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and sub-base.

### ABSTRACT

*The reuse of contaminated soils for geotechnical applications presents both environmental and engineering challenges. This study evaluates the influence of filter media thickness on the mechanical properties of electrokinetic remediated lead contaminated clay soil intended for road sub-base construction. Electrokinetic remediation (EKR) was carried out using filter media thicknesses of 0.5cm, 1.0cm, 1.5cm, and 2.0cm. Treated soils were subsequently compacted using West African Standard (WAS) and British Standard Heavy (BSH) methods to assess the effect of the compaction energy on soil densification and strength. The highest maximum dry (MDD) of 1.95g/cm<sup>3</sup> and least optimum moisture content (OMC) of 11% for WAS, was obtained at 1.5cm filter media thickness while MDD of 2.03g/cm<sup>3</sup> and OMC of 9.50% for BSH was also at 1.5cm filter media thickness. California Bearing Ratio (CBR) test for soaked and unsoaked were conducted to evaluate sub-base suitability, the best result for the soaked CBR at WAS and BSH compactive efforts were 6.95% and 10.60% at 1.5cm filter media thickness respectively, while for the unsoaked CBR for WAS at 2.0cm is 23.51% and for the BSH is 88.15%. Results indicated that filter media thickness and compaction energy significantly affect the MDD and CBR of the remediated soil. BSH compaction generally produced higher dry densities and bearing ratios than WAS, though optimal performance was achieved at moderate filter thicknesses. The findings demonstrate that appropriately designed EKR treatment coupled with suitable compaction standards can enhance engineering performance of contaminated soils for sustainable road construction in West Africa.*

### 1. INTRODUCTION

Soil contamination by heavy metals such as lead has become a pressing environmental issue, particularly in industrial, mining and urban areas where improper waste disposal, mining activities and vehicular emissions are prevalent (Alloway, 2013; Ogundiran and Osibanjo,

2008). Such soils often exhibit poor geotechnical and mechanical properties, limiting their use in civil engineering works (Akinwumi et al., 2017). Electrokinetic remediation (EKR) has emerged as an effective in-situ and ex-situ technique for the removal of heavy metals from fine-grained soils through the application of a low-intensity electric potential (Reddy and Cameslle, 2009). Beyond contaminant removal, EKR can also modify soil fabric, improve particle arrangement, and influence compaction behavior, all of which are critical for road sub-base performance (Alshawabkeh, 2019).

In west Africa, the West African Standard (WAS) of compaction is widely adopted for pavement material evaluation, while the British Standard Heavy (BSH) method is commonly referenced in international practice (FMWH, 1997; BS 1377, 1990). Both methods differ in the energy imparted during compaction, which directly affects the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), key indicators of soil strength and stiffness (Osinubi and Nwaiwu, 2005). Comparative studies between these two standards remain limited, especially when applied to electro-kinetically treated soils (Eze and Ijimdiya, 2020).

This research investigates how variations in filter media thickness influence the engineering suitability of lead-contaminated lateritic soil subjected to EKR treatment and subsequently compacted under WAS and BSH standards. The study aims to determine the optimal filter media thickness that maximizes density and bearing capacity while maintaining environmental safety for use as road sub-base material.

## **2. MATERIALS AND METHODS**

### **2.1 Materials**

#### *2.1.1 Lead Contaminated Soil (LCS)*

The lead contaminated soil (LCS) was collected at a depth of 1m from Awai mine site in Nassarawa state Nigeria, with the following coordinates N8.41'36"86'765" and E8.32'36"82'982", having a lead content of 142.3mg/kg which exceeds the allowable limits set by the WHO of 85mg/kg, and 60mg/kg by the US environmental protection agency. This necessitated the remediation of the LCS to improve its properties. The use of activated charcoal as a filter media at different thicknesses gave remarkable results. Representative samples were air-dried, pulverized, and sieved through a 4.75mm aperture size.

#### *2.1.2 Electrokinetic Remediation (EKR) Set-up*

The electrokinetic remediation setup that was used in this research is based on the model adopted by Yu et al., (2019). The system comprised an acrylic cell containing soil specimen, with graphite electrodes placed at the anode and cathode ends. A constant DC potential gradient with 30v until no effluent was collected at the cathode. The filter medium was installed adjacent to the electrodes at four thickness levels: 0.5cm, 1.0cm, 1.5cm, and 2.0cm. Distilled water combined with nitric and oxalic acid were used as electrolytes, and voltage, current, effluent and pH, variations were monitored throughout the process. Solar power setup was used to ensure continuous power supply to the setup.

#### *2.1.3 Activated Charcoal*

The activated charcoal used as filter media in this study was obtained at a chemical and science laboratory equipment shop located along Kano road, Kaduna.

## **2.2 Methods**

In accordance with BS 1377 (1990) "Methods of Tests for Soil used for Civil Engineering Purposes," as advised in the Nigerian General Specifications (1997) Clause 1050 ".

### *2.2.1 Compaction test*

Following remediation, the treated soils were subjected to West African Standard (WAS) and British Standard Heavy (BSH) compaction test to determine MDD and OMC in accordance with BS 1377: 1990 and FMWH (1997) procedures.

### *2.2.2 California Bearing Ratio (CBR)*

CBR tests were performed on the compacted samples to evaluate the load-bearing potential of each soil type under both standards. The test followed FMWH (1997) specifications for sub-base materials. CBR values were compared with standard sub-base requirements (CBR  $\geq$  30%).

## **3. RESULTS AND DISCUSSION**

The samples were air-dried and remediated at different filter media thicknesses of 0.5cm, 1.0cm, 1.5cm, and 2.0cm. According to AASHTO (1986) soil classification system, the soil falls under A-7-6 and falls into the CH group according to the Unified Soil Classification System (ASTM, 1992). It has a liquid limit of 42%, a plastic limit of 21.64%, a plasticity index of 20.36%, a specific gravity of 2.56, and of high swell potential according to NBRRI (1983) classification. These values show that the soil is highly plastic, with approximately 76.5% of the soil particles passing the BS. No 200 sieve. The strength characteristics are also very low, making the soil unsuitable for geotechnical engineering use. However, after remediation the soil fell into the A-5 and CL groups according to AASHTO and USCS soil classification systems respectively. The soil is considered to have low to medium compressible clays and is poor as a sub-grade material. The tables and figures shown and discussed below provides the results for the effects of compactive efforts at West African Standard (WAS) and British Standard Heavy (BSH).

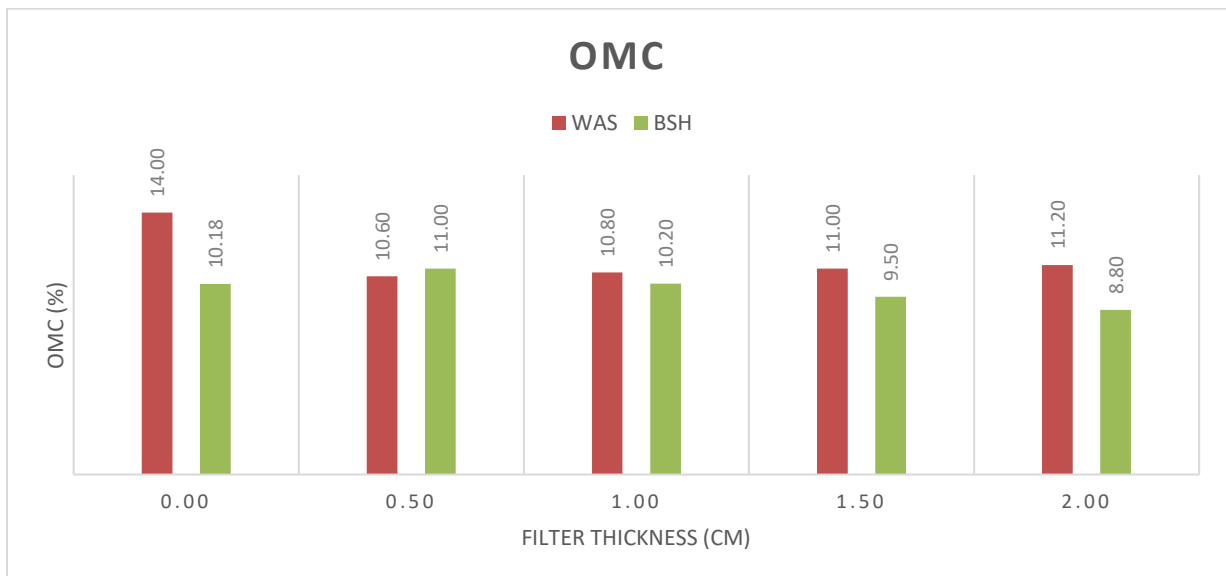
## **4.COMPACTION**

### **4.1 Maximum Dry Density**

The variations in Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the electrokinetically remediated soils under different filter media thicknesses and compaction standards are presented in the Figures 1 and 2 below.



**Figure 1.** Variation of MDD with filter media thickness under WAS and BSH



**Figure 2.** Variation of OMC with filter media thickness under WAS and BSH

A general trend was observed in which the MDD ( $1.95\text{g/cm}^3$  and  $2.03\text{g/cm}^3$  at WAS and BSH efforts) increased with increasing filter media thickness up to 1.5cm thickness, beyond which it slightly decreased to  $1.95\text{g/cm}^3$  and  $1.96\text{g/cm}^3$  at WAS and BSH respectively. This indicates that the thickness of the filter media affects the degree of electroosmotic consolidation and subsequent particle rearrangement within the soil. Under both compaction standards, BSH yielded higher MDD values than WAS due to the greater compactive effort, which enhanced particle interlock and reduced air voids. These findings align with those reported by Muntohar and Liao (2010) which showed that increasing filter media thickness improves the soil MDD and reduces the OMC. It is also supported by Salahudeen et al. (2014) on the properties of lead contaminated soils in Nigeria and the effect of remediation using various methods.

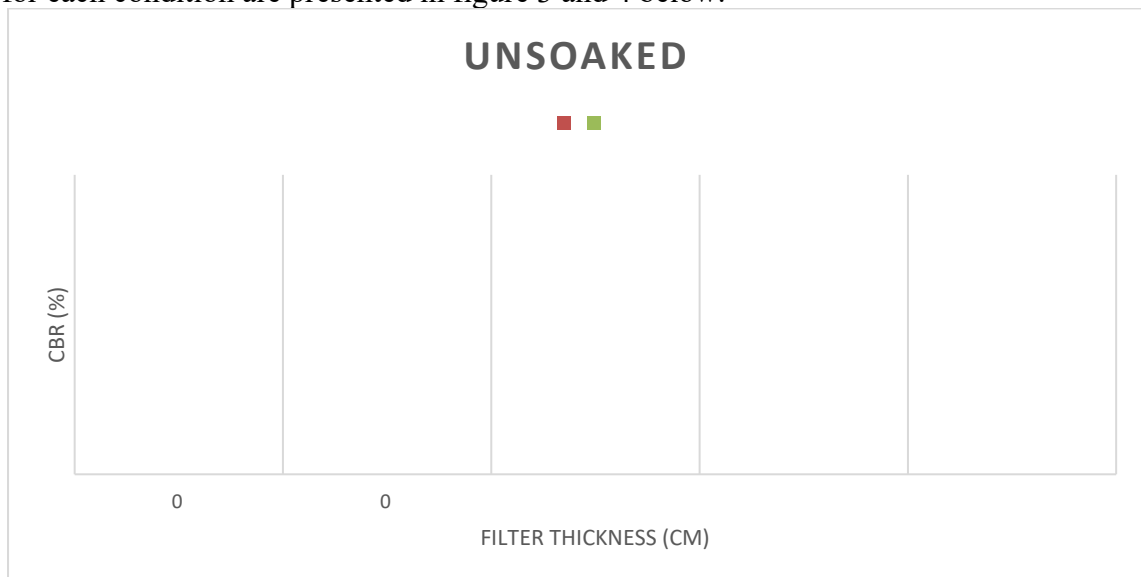
OMC values were slightly lower under BSH, at 1.5cm the OMC was 11% and 9.5% for WAS and BSH respectively, reflecting the soil's reduced water demand for achieving maximum density. This observation aligns with findings by Ola (1983) and Osinubi et al. (2015), who reported that higher compactive effort results in reduced OMC and increased MDD for lateritic soils. The OMC experiences a slight increase at 2.0cm filter thickness this may be as a result

of thick filters reducing electroosmotic efficiency due to increased current path length and lower voltage gradients, leading to marginally lower MDD and OMC values.

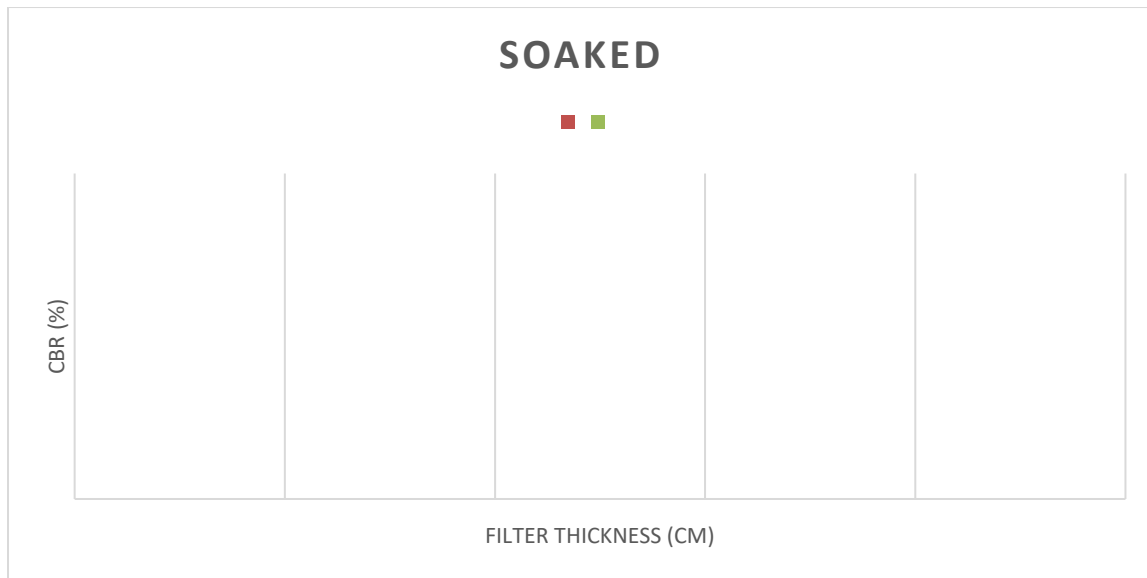
The influence of EKR treatment is evident at optimal filter thickness (typically around 1.5-2.0cm), the migration of ions and water led to improved particle bonding, thus facilitating higher densities during compaction.

#### **4.2 California Bearing Ratio (CBR)**

The LCS recorded 4.0% and 21.16% for both the soaked and un-soaked respectively. The highest CBR value was recorded at 1.5cm filter media thickness with 88.15% and 10.60% for both the un-soaked and soaked with higher compaction energy (BSH) aligns with the standard requirement for adequate compaction to achieve necessary strength and stability. Thicker filter media enhances CBR values, indicating better load distribution and stability, which is a criterion for performance. The un-soaked CBR values obtained at the British standard Heavy (BSH) energy compaction at 1.0cm, 1.5cm and 2.0cm activated charcoal filter media thickness of 75.59%, 87.92%, and 88.15% meets the 80% minimum requirement for a Type 1 base or sub-base materials while the values obtained at the West African Standard compaction energy for the un-soaked for filter media thickness at 0.5cm, 1.5cm and 2.0cm which are 28.58%, 22.76% and 23.51% meets the minimum requirement for Type 2 sub-base material for light trafficked roads. According to the Nigerian General Specifications (1997) for Roads and Bridges, the minimum California Bearing Ratio (CBR) value for subgrade materials for highways and major roads, the minimum requirement for subgrade material is 10% when tested un-soaked condition while for minor roads or less trafficked roads, the minimum CBR is generally 5-7%. The soaked CBR value (10.60) peaked at 1.5cm filter media thickness and at BSH energy, this value met the minimum of 10% requirement for a subgrade material for a minor road. The impact of higher energy levels did not impact any significant improvement on the un-soaked CBR value of the EKR lead contaminated soil, this is consistent with what was reported by Moses (2007). The reduction in CBR values when soaked underscores the need to consider moisture content and drainage, as stipulated by standards. The values for each condition are presented in figure 3 and 4 below.



**Figure 3.** Variation of CBR values with filter media thickness under WAS and BSH (un-soaked)



**Figure 3.** Variation of CBR values with filter media thickness under WAS and BSH (soaked)

Notably, all treated soils compacted BSH energy met or exceeded the minimum CBR requirement of 30% (un-soaked) specified by FMWH (1997) for sub-base materials. In contrast, WAS-compacted samples did not achieve satisfactory performance across all the filter media thicknesses, suggesting the use of higher compactive energy ensures better engineering reliability.

## 5. RECOMMENDATION

For field applications, the filter media thickness of 1.5cm at BSH energy is recommended as optimal, balancing treatment efficiency, energy consumption, and mechanical performance. Further research should explore the use of EKR and the effects of activated charcoal and its efficiency in removing other heavy metals from lateritic soils.

## 6. CONCLUSION

The comparative analysis between the West African and British Heavy compaction standards demonstrates that the choice of compaction method significantly affects the engineering behavior of the electrokinetically remediated soils. Although BSH compaction achieved superior densification and CBR values, the WAS method still produced some acceptable results, implying that locally adopted compaction standards remain viable for subgrade construction if EKR process is optimized. Electrokinetic remediation significantly improved the compaction characteristics and bearing strength of lead-contaminated clay soil. Integrating EKR treatment with suitable compaction procedures offers a cost-effective and sustainable approach.

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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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## GREEN MINING FOR SUSTAINABLE MINING IN NIGERIA

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### ABSTRACT

*Green mining refers to technologies, best practices and processes that reduce environmental impacts while ensuring efficient mineral resource extraction. Mining operations always impact negatively the natural environment, economy and social structure of the area where mineral extraction takes place. The goal of green mining, therefore, is to minimise the adverse environmental and social impacts in all stages of the operations. Nigeria, endowed with significant mineral resources, faces significant environmental degradation due to traditional mining practices over the decades. Green mining technology offers a sustainable alternative, enabling environmentally responsible mineral extraction while promoting economic development. It is believed that Nigeria's mineral sector holds tremendous potential to diversify the national economy beyond oil dependence. However, mining practices, particularly in artisanal and small-scale operations, contribute heavily to land degradation, water pollution and deforestation. To align with global sustainable development goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), Nigeria must transition to green mining practices. This paper explores the application of green mining technologies in Nigeria, assesses current practices, evaluates environmental and socio-economic impacts and proposes strategies for implementation. Key technologies such as bioremediation, water treatment, renewable energy use and automated monitoring systems are examined in the Nigerian context.*

### 1.0 INTRODUCTION

As the world begins to demand greater environmental accountability, mining operations in many countries around world are implementing technologies that reduce the environmental footprint throughout the lifecycle of the mining enterprise. Green mining, also known as environmentally sustainable mining, aims to reduce the environmental footprint and promote responsible resource extraction. The environment is not just a backdrop to economic activity; it's the foundation of life itself encompassing land, water and air – basic supporting ingredients of life. Rivers provide water for agriculture; forests on land sustain biodiversity and clean air sustains life and keeps humans healthy.

Neglecting these resources for short-term gains is like removing the ladder after climbing up. Neglecting the environment therefore is shortsightedness and foolhardy.

Modern mining practices and technologies can minimize environmental damage while maximizing economic benefits at the same time. On one side lies the promise of boundless economic growth, driven by its vast mineral resources; on the other hand, there is a pressing need to protect our environment from irreversible damage which can result from irresponsible mining activities. However, with the right strategies, Nigeria can harmonise economic advancement with environmental preservation by adopting green mining practices—a true win-win scenario that benefits both the present and future generations.

## **2. HISTORICAL BACKGROUND ON USE OF ENERGY**

Nearly all energy used before the 19<sup>th</sup> century, was renewable. The oldest known use of renewable energy, in the form of traditional biomass to fuel fires, dates from more than a million years ago. The use of biomass for fire did not become commonplace until many hundreds of thousands of years later (Kris, 2013). Probably the second oldest usage of renewable energy is harnessing the wind in order to drive ships over water. This practice can be traced back some 7000 years, to ships in the Persian Gulf and on the Nile. From hot springs, geothermal energy has been used for bathing since Paleolithic times and for space heating since ancient Roman times (Geothermal Energy, 2017). Moving into the time of recorded history, the primary sources of traditional renewable energy were human labour, animal power, water power, wind in grain crushing windmills and firewood a traditional biomass. In the 1970s environmentalists promoted the development of renewable energy both as a replacement for the eventual depletion of oil, as well as for an escape from dependence on oil and the first electricity-generating wind turbines appeared.

## **3. ROLE OF GREEN MINING IN ADDRESSING CLIMATE CHANGE**

The terms “green” and “mining” haven’t traditionally sat comfortably together but things are starting to change. As a developing country, robust mining can provide revenues to fund critical infrastructure, create millions of jobs and boost GDP growth. But these benefits from mining must not come at the expense of our land, water and air. If we destroy the environment in pursuit of wealth or development, we lose far more than we gain. As we progress through the 21<sup>st</sup> century, the importance of green energy in shaping our modern world cannot be overstated. Many countries and mining companies have acknowledged the challenge and have stated their commitment to the values of sustainability. Nigeria should do the same because Nigeria is not immune from the negative impact of mining on the environment, especially emission of greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O etc.).

## **4. OVERVIEW OF ENVIRONMENTAL IMPACTS OF TRADITIONAL MINING IN NIGERIA**

Traditional mining practices have long been associated with significant environmental impacts in Nigeria, including: Blasting and excavation, resulting in land disturbance and ground vibration; Habitat destruction and deforestation; Land degradation and Soil erosion; Air and water pollution; Waste generation and the release of chemicals and heavy metals into the environment. Some of mining activities that have caused pollution are discussed below:

### **4.1 Sedimentation and Erosion**

Mining that involves removing overburden and scraping away rocks to get the mineral buried near the surface, leads to the destruction of agricultural lands and erosion of soil. Plants, trees and topsoil are scraped away from the mining area and destroy wildlife habitats and landscapes. When these mining

sites experience heavy rain, the loosened topsoil is washed away, carrying sediments that may pollute the streams, lakes and rivers. Excessive residue can harm aquatic organisms and watershed vegetation downstream. Moreover, it can also cause disfiguration of streams and river channels, which results in flooding.

#### **4.2 Water Pollution**

Water is essential to life on our planet. A prerequisite of sustainable development must be to ensure uncontaminated streams, rivers, lakes and oceans. The mining and processing of mined materials generally require water. Water is also the primary vehicle by which mining-related contaminants can inadvertently be transported into the environment and worsen the quality of water resources. Mining water pollution has severe consequences for wildlife and human life. Protecting endangered species and maintaining clean water sources are crucial for sustaining biodiversity, ensuring human health and well-being. Prevention of water quality degradation is an important step in ensuring environmental sustainability in mining areas.



**Figure 1.** Polluted section of the Osun river from artisanal gold mining activities, Osogbo (Source: Eromo Egbejule and Festus Iyora. Published On 2 Sep 2022)

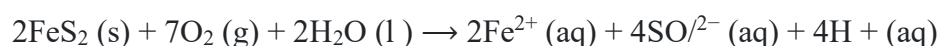


**Figure 2.** Polluted water bodies at mining sites, near Abakaliki, Ebonyi state. (Source: SOFRECO/Beak consultants, MMSD, 2019)

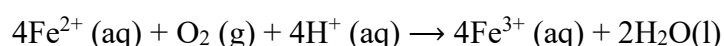
### 4.3 Acid Mine Drainage

Acidic discharges from active or abandoned mines are called *acid mine drainage* (AMD) or acid rock drainage (ARD). Acid mine drainage is the formation and movement of highly acidic water rich in heavy metals. This acidic water forms through the chemical reaction of water with rocks that contain sulphur-bearing minerals, resulting in sulphuric acid. The pH of AMD is usually in the range of 2–6. Some or all of this iron can precipitate to form the red, orange, or yellow sediments in the bottom of streams.

- (i) *Acid Mine Drainage (AMD)*: When sulphide-containing rocks are exposed to air and water, they can react to form sulphuric acid, which can leach into groundwater and surface water, polluting it with heavy metals and acid.
- (ii) *Chemistry of AMD*: Although a host of chemical processes contribute to acid mine drainage, pyrite oxidation is by far the greatest contributor. A general equation for this process is:



The oxidation of the sulphide to sulphate solubilizes the ferrous iron (iron(II)), which is subsequently oxidized to ferric iron (iron(III)):



Either of these reactions can occur spontaneously or can be catalyzed by microorganisms that derive energy from the oxidation reaction. The ferric cations produced can also oxidize additional pyrite and reduce into ferrous ions. The net effect of these reactions is to release  $\text{H}^+$ , which lowers the pH and maintains the solubility of the ferric ion.

- a) *Heavy Metal Contamination*: Mining operations release heavy metals like arsenic, lead, mercury and zinc into the environment, which can contaminate water sources and leach into the soil.
- b) *Tailings and Waste Rock*: Mining processes generate vast amounts of waste, including tailings (material left over after ore processing) and waste rock. These materials can contain toxic substances and heavy metals that can leach into soil and groundwater.
- c) *Processing chemicals pollution*: Mining companies generally use chemical compounds such as sulphuric acid or cyanide to separate their respective target minerals from the ore. Contamination occurs when these chemicals are leached, leaked, or spilled from the mining area into the nearby bodies of water; contaminating water sources and harming aquatic life. These chemicals are highly toxic and could lead to loss of life on wildlife species and severe health concerns on the human body.



**Figure 3.** Left: River pollution by acid mine drainage. Right: Polluted river after cleaning

An analysis of water quality in Onyema and Okpala mine districts in Enugu, Southeast, Nigeria was reported by mean values of heavy metals namely; Cadmium, Arsenic, Lead, Chromium were respectively reported as 0.33mg/l, 0.06 mg/l, 0.53mg/l and 0.06 mg/l with mean pH values of 5.4 all of which exceeded the WHO permissible limits of 0.0-5.0mg/l for all the metals identified.. It was also reported that total dissolved solids (TDS) values ranging between 21.80 and 520 mg/l were below WHO permissible limits of 0.00-1500 mg/l but however injurious to the aquatic life in the catchment (Ojonimi, 2020).



Figure 4: Reprocessing of gold using cyanide at Uke gold mining site (Source: SOFRECO/Beak consultants, MMSD, 2019)

#### **4.4 Air Pollution**

Air pollution from mining activities is a significant concern, affecting both the environment and human health. Mining releases particulate matter (PM), gases, and toxic metals into the air, contributing to respiratory problems, cardiovascular diseases, and other health issues for workers and nearby communities

- (i) *Dust and Particulate Matters*: Mining activities, such as blasting, hauling and smelting, generate dust and particulate matters that can be released into the atmosphere, impacting air quality and potentially affecting human health.
- (ii) *Gases*: Blasting operations release gases like carbon dioxide, nitrogen oxides, and sulfur dioxide into the atmosphere.
- (iii) *Smelting Emissions*: Smelting, the process of extracting metals from ore, releases toxins like lead, mercury and sulphur dioxide into the atmosphere.

#### **4.5 Soil Pollution**

Soil pollution from mining activities is a significant environmental concern, affecting ecosystems, human health and food security. Mining releases toxic metals, chemicals and waste, contaminating soil and posing long-term risks.

- a. *Heavy Metal Contamination*: Mining activities can contaminate soil with heavy metals, making it unsuitable for agriculture and impacting plant and animal life.
- b. *Tailings and Waste Rock*: Tailings and waste rock can be deposited on land, contaminating the soil with toxic substances and heavy metals.



Figure 5: Primary processing of gold at Uke mining site, Nasarawa state  
(Source: SOFRECO/Beak consultants, MMSD, 2019)

#### 4.6 Habitat Destruction and Biodiversity Loss

Habitat destruction and biodiversity loss are significant environmental concerns associated with mining activities. Mining can lead to deforestation, habitat fragmentation, and loss of ecosystems, threatening species and ecosystems.

*Deforestation:* Mining operations often require clearing large areas of land, leading to deforestation and habitat destruction.

#### 4.7 Fire-setting

Fire-setting is a method of traditional mining used most commonly from prehistoric times up to the Middle Ages. Fires were set against a rock face to heat the rock, which was then doused with water or any other kind of liquid, causing the rock to fracture by thermal shock. In some places where some communities are nearby, fire setting is still used to avoid consequences of use of explosives. A good example is fire-setting activities at Magnet quarry, Kaduna (Figure 4:6)



Figure 6. Fire-setting activities at Magnet quarry, Kaduna  
(Source: Lawal, 2024)

Although fire-setting was frequently used before modern times, it has been used sporadically since then. The artisanal miners set fire on the rock mass to weaken its strength. Water is then sprayed on the rock to cool it. The effect of heating and cooling (expansion and contraction) leads to cracking of

the rockmass. The already weakened rockmass is then broken into smaller pieces using hammer and chisel. This practice is common in some areas in the country especially where big operators have ceased working or places where blasting operations cannot be carried out. Example Malali in Kaduna

#### 4.8 Waste from mining process

An ore is a mineralized rock containing valued metal(s) such as gold or copper. Mining involves the excavation of large quantities of waste rock in order to extract the desired mineral. The ore is then crushed into finely ground particles for separation of valuable minerals from non-valuable components that are discarded as tailings or waste. Similar wastes are also generated from other minerals other than ores, for instance coal resources, non-metallic or industrial minerals.

### 5. TRANSITION TO SUSTAINABLE DEVELOPMENT

Nigeria is a signatory to many of the protocols or agreements on globalization, social and environmental concerns. Green energy is important for the environment because it can replace the negative effects of fossil fuels (emission of greenhouse gases e.g. CO<sub>2</sub>, CH<sub>4</sub>. Clean energy are those types which do not release pollutants into the air and renewable energy comes from sources that are constantly being replenished, such as hydropower, wind power or solar energy. Sustainable development is progress and transformation that meets the needs of the present without compromising the ability of future generations to meet their own needs. It is critical that no one is left behind. The transition to sustainable development is primarily grounded in a series of international agreements and goals that are then implemented at the level of the individual states and communities involved. Among these, the best known are: The *United Nations Framework Convention on Climate Change* and its protocols, which set commitments to reduce greenhouse gas (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O etc.) emissions;

1. The *Convention on Biological Diversity (CBD)*, which promotes the conservation of biodiversity; and,
2. More importantly, the UN Sustainable Development Goals (SDGs), which cover a wide range of sustainability issues. Built around these goals is the UN 2030 Agenda, a plan of action for people, planet and prosperity, signed into law by the UN General Assembly on September 25, 2015. The Agenda includes 17 goals, valid for everyone around the world, articulated along the three dimensions of sustainable development: economic, social and environmental.



Figure 7. Sustainable Development Goals (SDG, 2015)

### 6. ENERGY TRANSITION PLAN FOR NIGERIA

Energy transition refers to the global energy sector's shift from fossil-based systems of energy production and consumption — including oil, natural gas and coal — to renewable energy sources. In 2021, Nigeria's Energy Transition Plan (ETP) was created with COP26 support, prompting Nigeria's

net-zero commitment by 2060. The plan has government approval and presents a \$23 billion opportunity for supporting financiers and partners. The plan maps a pathway to reduce Nigeria's dependence on hydrocarbon sources, emphasizing renewable energy. The plan aims for net-zero emissions by 2060 and proposes gas commercialization until 2030, then a gradual fossil fuel phase-out. The plan aims to reduce Nigeria's greenhouse gas emissions and improve air quality. It estimates that the transition could reduce Nigeria's greenhouse gas emissions by up to 45% by 2030 and up to 90% by 2050. The plan is expected to create significant economic opportunities and job creation across various sectors of the economy, including renewable energy, energy efficiency and electric vehicles. This is a possibility that 5 million new jobs could be created by 2030. Estimates are that US\$1.9 trillion will be invested in the sector by a full transition in 2060. This includes initiatives to support developing sectors like electric mobility, green hydrogen and capacity-building for the creation of new markets. There is a need for policy and regulatory change mainly aimed at creating a conducive environment for businesses to invest in energy transition. There is also a need for significant capacity building and skill development to support roll-out and growth of new technologies.

## **7. DEVELOPMENT OF NIGERIA'S MINERAL RESOURCES**

Nigeria is blessed with abundant mineral resources including:

- |  |  |
|--|--|
| a. Precious metals (Gold, Silver etc.),  | s. Green Energy Minerals/Metals          |
| b. Metallic Minerals (Cassiterite, Tantalite,  | (Lithium, Tin, Cobalt, Nickel, Graphite, |
| c. Iron ores, Columbite, Lead/Zinc Sulphides,  | t. Copper,                               |
| d. Chromite,   | u. Aluminium,                            |
| e. Copper ores,  | v. Manganese,                            |
| f. Molybdenite,  | w. Neodymium,                            |
| g. Manganese, Wolframite,  | x. Zinc,                                 |
| h. Bismuthine etc.), Industrial Minerals & Dimension stones/Construction minerals (Clays, Barytes, | y. Rare Earth Elements                   |
| i. Gypsum, Feldspar, Limestone/Marble, Kaolin,   | z. etc.                                  |
| j. Talc,   |  |
| k. Mica,   |  |
| l. Diatomite,  |  |
| m. Sand,   |  |
| n. Phosphate,  |  |
| o. Soda ash,   |  |
| p. Granite   |  |
| q. Gemstones (Amethyst, Aquamarine, Tourmaline, Garnet, Zircon, Sapphire etc),                     |  |
| r. Fossil Fuels (Coal, Tar sands),   |  |

The *grundnorm*, that is, the fundamental rule or principle that underpins the Nigerian mining law and serves as the basis for all other laws in the development of minerals in the country is the Nigerian Minerals and Mining Act (NMMA), 2007. The NMMA is the most important law on which all other laws, such as, the *Regulations*, policies are based.

## 8.0 Green Mining Technologies

The concept of “green mining” is no longer a futuristic fantasy—it’s happening worldwide. From renewable energy-powered operations to advanced waste recycling systems, mining companies have access to a suite of eco-friendly tools. One of the core principles of green mining is the transition to renewable energy sources for mining operations. Instead of relying on fossil fuels, which contribute to climate change, green mines are adopting solar, wind and hydropower technologies to power their operations. In general, mining techniques have become much more environmentally sensitive when efficiency is improved because less waste is produced.

Green mining techniques include in situ leaching and bio-mining, which reduce surface disruption and energy use. Other key practices involve integrating renewable energy, using energy-efficient and electric/hybrid equipment, and improving water and waste management through methods like closed-loop recycling and waste reuse. Advanced technologies such as digitalization, automation, and carbon capture also contribute to sustainability.

- a) *In-situ mining and bioleaching*: Green mining embraces innovative techniques, like *in-situ* recovery and bioleaching, which minimize surface disruption and reduce environmental footprint. These methods are particularly useful for extracting minerals from ore bodies that are hard to access through traditional means.
- b) *Bioremediation*: Use of microorganisms to detoxify polluted soils and water in mining areas. This can be applied post-mining to restore ecosystems affected by heavy metals.
- c) *Use of electric vehicles*: The use of advanced equipment, such as electric vehicles and energy-efficient machinery. The deployment of electric haul trucks and processing units is a key component of green mining technology, offering a practical solution for reducing greenhouse gas emissions associated with mineral extraction and processing. Traditional diesel-powered mining machinery contributes significantly to CO<sub>2</sub> emissions, air pollution, and operational costs. Replacing these with electric-powered alternatives enhances environmental sustainability and improves operational efficiency.
- d) Renewable energy sources like solar and wind power are also being integrated into mining operations to reduce reliance on fossil fuels. In addition, solar and wind power have the advantage is that electric mining equipment can be powered by renewable energy, especially solar. Nigeria’s abundant solar radiation makes it ideal for charging battery-electric mining vehicles. These renewable energy sources can also power processing machinery at artisanal mining sites by creating mini-grids to support mining clusters with clean and stable electricity. This integration would significantly reduce the use of diesel, which is both expensive and environmentally harmful. These will align with Nigeria’s Energy Transition Plan (ETP) aiming for net-zero emissions by 2060.

## 9. CHALLENGES TO IMPLEMENTATION

Despite the advantages, several barriers must be addressed:

*High Capital Costs*: Importing electric mining equipment can be cost-prohibitive for small and medium mining enterprises.

*Infrastructure Deficiency*: Lack of charging infrastructure, spare parts, and trained technicians limits large-scale adoption.

*Policy Gaps:* There is currently no national incentive for mining firms to adopt electric equipment or switch to renewable energy.

*Resistance to Change:* Many operators are unfamiliar with the benefits or technical requirements of electrification.

### **9.1. Water Management, Conservation and Treatment**

Green mining emphasizes water conservation and efficient management practices. Mining operations can significantly impact local water resources, leading to water scarcity and pollution. Mines can implement strategies to minimize water consumption by recycling and reusing water wherever possible. Furthermore, advanced water treatment technologies are being employed to ensure that any discharged water is clean and safe for the environment.

### **9.2. Sustainable Materials Handling**

Efficient materials handling is essential for minimizing waste and reducing the environmental impact of mining. Innovations help increase resource recovery rates. For example, bulk ore sorting separates valuable minerals from waste early in the process.

### **9.3. Selective Mining and *in-situ* mining**

Selective mining involves extracting only high-grade materials, leaving lower-grade ores in place. This approach reduces waste generation and decreases the amount of material that needs to be processed, minimizing the overall environmental impact. Therefore, do selective mining first and follow it by doing *in-situ* mining

**9.4. Ecosystem Restoration:** Traditional mining often leads to the destruction of natural habitats and biodiversity loss. Green mining seeks to restore ecosystems impacted by mining activities. After the closure of mining operations, reclamation efforts are undertaken to rehabilitate the land and support the return of native flora and fauna.

*Reprocessing of tailings:* Sometimes amounts of the metals being mined end up in the wastes. Reprocessing these wastes can result in more usable material.

*Dust suppression techniques:* During the mining process, large amounts of dust are released into the atmosphere. This can be minimized by pre-wetting the areas to be blasted with high volume sprinklers. Dust in the air, can also be removed through mist cannons (very high-volume water sprinklers).

*Liquid membrane emulsion technology:* This is a separation technique that can be used to extract usable metal from highly toxic or acidic waste water produced by a mine. This technology can even deal with dilute solutions

*Choice of ventilation system and diesel engines:* 10 percent of mining costs come from electricity consumption. Better ventilation systems and diesel engines can maximize efficiency in mining operations.

### **9.5 Community Engagement and Social Responsibility**

Green Mining recognizes the importance of engaging with local communities and respecting their rights. It involves the creation of sustainable livelihoods, fostering economic opportunities, and investing in social development projects. This approach not only improves the quality of life for nearby

communities but also ensures the long-term success of the mining operation by gaining community support.

## **10. CHARGING TOWARDS THE FUTURE**

The green mining technology is still in the early stages, with many of these technologies still in concept stages and as with most emerging technologies, the only foreseeable way that large-scale transition can occur will require government incentives and a potentially a move towards a price on carbon and/or other pollutants. The path to a better tomorrow is rarely easy, but Nigeria has what it takes to walk it. By prioritizing both economic growth and environmental preservation, we can secure a legacy of prosperity and sustainability for future generations. The time to act is now. Let's build a future where Nigeria's mining industry sets the gold standard for the world.

Green mining can offer many benefits in the exploitation of Nigeria's mineral resources. These include:

- a) *Environmental Conservation*: Green mining practices minimize the negative environmental impacts of mining, such as deforestation, water pollution, and soil degradation. This is achieved through sustainable mining technologies, reclamation strategies, and waste management techniques.
- b) *Job Creation and Economic Growth*: The mining industry provides employment opportunities and stimulates local economies, contributing to economic growth and development. Green mining can ensure that these benefits are sustained while minimizing harm to the environment.
- c) *Improved Community Engagement*: Green mining encourages mining companies to engage with local communities, ensuring they benefit from mining activities through job creation, infrastructure development and social programmes.
- d) *Reduced Carbon Footprint*: The adoption of green technologies, such as solar and wind energy, can significantly reduce the carbon footprint of mining operations. For example, the Gold Fields Tarkwa Mine in Ghana has installed a 40 MW solar power plant to reduce dependence on fossil fuels.
- e) *Increased Investment Attraction*: African countries are attracting investments in green mining initiatives, local empowerment and environmental protection. The World Bank's Africa Mining Project has invested over \$300 million to support sustainable mining practices (Future of Mining, 2025).
- f) *Water Conservation*: Green mining practices prioritize water conservation and efficient use, reducing the risk of water contamination and ensuring that local communities have access to clean water.
- g) *Land Rehabilitation*: Mining companies are encouraged to restore land to its original state or repurpose it for sustainable uses after mineral extraction. This includes replanting trees, rebuilding topsoil and ensuring that water resources are clean and available for local communities. Overall, green mining offers a more sustainable and responsible approach to mineral exploitation, balancing economic benefits with environmental and social responsibility.

## **11. CHALLENGES AND OPPORTUNITIES**

Green mining in Nigeria faces challenges like a lack of funding, inadequate infrastructure, complex regulations, and security risks, but also presents opportunities for attracting investment, improving the environment, and fostering sustainable development. Overcoming these obstacles requires addressing the regulatory, financial, and security issues while capitalizing on the potential for eco-friendly innovation and investor incentives.

- a) *Regulatory Frameworks*: Strengthening regulatory frameworks can encourage the adoption of green mining technologies.
- b) *Research and Development*: Investing in R&D can help develop context-specific green mining technologies for Nigeria's mining industry.
- c) *Training and Capacity Building*: Providing training and capacity-building programs can enhance the skills of mining professionals in green mining technologies.

## 12. CONCLUSION

To ensure that Nigeria's mining sector remains a driver of economic growth without compromising environmental sustainability, there is a need for continued investment in green mining technologies and practices. Nigeria must collaborate with global partners, share knowledge and build capacity to develop a sustainable mining sector that contributes to both the green energy transition and the country's development goals.

Ultimately, the path to sustainable mining in Nigeria lies in the careful balance between harnessing the country's mineral wealth and protecting the environment. Through innovative solutions, regulatory reforms and increased community involvement, the giant of Africa can lead the way in sustainable mining for the green energy future. By prioritising environmental protection and sustainable practices, Nigeria can ensure that its mineral resources benefit not only the global green energy transition but also its own communities for generations to come.

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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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## LITHIUM-ION ENRICHMENT FLOWSHEET FOR NIGERIA'S LITHIUM ORE

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### ABSTRACT

*The demand for lithium minerals has increased considerably in recent years due to the application of lithium compounds in renewable energy systems. Spodumene is the main lithium bearing mineral which is currently being exploited in Nigeria due to its high lithium content and the extensive occurrence of deposits across pegmatitic regions of the country. This paper focuses on the techniques used in the beneficiation of lithium minerals from hard rock pegmatite ores with special focus of flotation process and the production of lithium ion ( $\text{Li}^+$ ) using the electrolytic process. Flotation technique is used as a process route for the separation of lithium minerals from the ores even though dense medium separation (DMS) offers an alternative. The close similarity in chemical and physical properties between lithium minerals and associated gangue minerals complicates the beneficiation of lithium minerals from ores. Surface chemistry of minerals, type of collector, pulp pH, chemical pre-treatment methods and the presence of slimes play key roles, hence the choice of flotation technique. For the secondary processing, electrolytic process is discussed to produce any of lithium compounds including lithium carbonate ( $\text{Li}_2\text{CO}_3$ ), lithium oxide ( $\text{Li}_2\text{O}$ ), and lithium hydroxide ( $\text{LiOH}$ ). Conventional and common lithium metal extraction has typically involved acid or alkaline [leaching](#) of lithium-containing ores (spodumene) is used to dissolve the lithium from the spodumene concentrate, followed by extraction of the metal, concentration of the lithium solution and then conversion to [lithium ion in the form of lithium carbonate, lithium oxide](#) or [lithium hydroxide](#) using the electrolytic process.*

### 1. INTRODUCTION

Energy is a big deal and the world is witnessing a rapid shift towards a cleaner and more sustainable energy future. Governments, corporations and individuals have recognized the urgent need to address the impacts of climate change and therefore, there is a growing demand for energy sources

that are less carbon-intensive. The current energy transition therefore is the shift from hydrocarbon sources (including oil, natural gas and coal) to renewable and cleaner energy sources in order to reduce greenhouse gas (carbon dioxide, methane etc.) emissions and combat climate change.

### **1.1 Link between energy transition and critical mineral resources.**

The energy transition is intricately linked with critical mineral resources or elements, which are essential for powering clean energy technologies like solar panels, wind turbines and electric vehicle batteries. Critical minerals are minerals that are essential to the economy and national security of a country, but whose supply chain is vulnerable to disruption (IEA, 2022). An energy system powered by clean energy technologies differs profoundly from one fuelled by traditional hydrocarbon resources. Building solar photovoltaic (PV) plants, wind farms and electric vehicles (EVs) generally requires more minerals than their fossil fuel-based counterparts. A typical electric car requires six times the mineral inputs of a conventional car and an onshore wind plant require nine times more mineral resources than a gas-fired power plant. Since 2010, the average amount of minerals needed for a new unit of power generation capacity has increased by 50% as the share of renewables has risen. The types of mineral resources used vary by technology. Lithium, nickel, cobalt, manganese and graphite are crucial to battery performance, longevity and energy density. Rare earth elements are essential for permanent magnets that are vital for wind turbines and EV motors. Electricity networks need a huge amount of copper and aluminium, with copper being a cornerstone for all electricity-related technologies (IEA,2022). One of the most important minerals/elements is lithium, which is crucial for battery storage, with demand expected to increase by 488% to meet future needs (The IEA, 2020). It is a surprise that the world's demand for lithium exploitation is growing every day and is especially driven by an increased lithium use in new consumer electronic battery technologies and electric cars (Clarke, 2013).

### **1.2 Enrichment flowsheet for Lithium ion**

By developing an enrichment flowsheet, mining investors in the Nigerian mining industry can optimise their lithium mineral processing and lithium metal extraction operations, leading to improved efficiency, reduced costs and increased profitability. In addition, efficient and sustainable practices in the mining industry are a boost to Nigeria's Energy Transition Plan (ETP) which was created in 2021 with COP26 support, prompting Nigeria's net-zero commitment by 2060. The plan has government approval and presents a \$23 billion opportunity for supporting financiers and partners (Damisa, 2024).

Lithium is a chemical element with the symbol Li and atomic number 3. It is a soft, silvery-white alkali metal. Under standard conditions, it is the least dense metal. It is an alkali metal and like all alkali metals, lithium is highly reactive and flammable (Garrett, 2004) Therefore, it must be stored in vacuum, inert atmosphere, or inert liquid such as purified kerosene or mineral oil. It is widely employed in various important applications such as lithium-ion batteries, glass, ceramic, metallurgy, lubricant, nuclear energy, and organic chemistry due to its high electrochemical activity, specific heat capacity, redox potential and other excellent properties. When cut, it exhibits a metallic lustre, but moist air corrodes it quickly to a dull silvery gray, then black tarnish. It never occurs freely in nature, but only in (usually ionic) compounds, such as pegmatitic minerals. Due to its solubility as an ion, it is present in ocean water and is commonly obtained from brines. Lithium metal is isolated electrolytically from a mixture of lithium chloride and potassium chloride (Haynes, 2014).

The alkali metals are also called the lithium family, after its leading element. Like the other alkali metals (which are sodium (Na), potassium (K), rubidium (Rb), caesium (Cs), and francium (Fr)), lithium has a single valence electron that is easily given up to form a cation (Krebs, 2006). Because of this, lithium is a good conductor of heat and electricity as well as a highly reactive element, though it is the least reactive of the alkali metals. (Lithium, Britannica encyclopedia, 2020). Lithium's low reactivity is due to the proximity of its valence electron to its nucleus (the remaining two electrons are in the 1s orbital, much lower in energy, and do not participate in chemical bonds)(Krebs, ). Molten lithium is significantly more reactive than its solid form (Handbook of Chemistry & Physics ,2017).

### **1.3 Lithium and its compounds**

Lithium and its compounds have several industrial applications, including heat-resistant glass and ceramics, lithium grease lubricants, flux additives for iron, steel and aluminium production, lithium batteries, and lithium-ion batteries. These uses consume more than three-quarters of lithium production. (Emsley, 2011) and (Jefferson, 2014)

Although lithium is widely distributed on Earth, it does not naturally occur in elemental form due to its high reactivity. (Krebs, 2006). The total lithium content of seawater is very large and is estimated as 230 billion tonnes, where the element exists at a relatively constant concentration of 0.14 to 0.25 parts per million (ppm), or 25 micromolar; higher concentrations approaching 7 ppm are found near hydrothermal vents.(Lithium Occurrence, 2009.). Estimates for the Earth's crustal content range from 20 to 70 ppm by weight. Lithium constitutes about 0.002 percent of Earth's crust (lithium: Britannica encyclopedia, 2020).

In keeping with its name, lithium forms a minor part of igneous rocks, with the largest concentrations in granites. Granitic pegmatites also provide the greatest abundance of lithium-containing minerals, with spodumene and petalite being the most commercially viable sources, (Garrett, 2004) Pegmatites are intruding rock units which form when mineral-rich magma intrudes from magma chambers into the crust. Pegmatites are commonly zoned, coarse-grained intrusive igneous rocks that form in the late stages of magma crystallisation and mostly have an overall granitic composition. Pegmatite is an exceptionally coarse-grained plutonic igneous rock. Most pegmatites have a mineralogical composition of granite but composition has no defining importance here. Pegmatites may have any imaginative magmatic composition and they are actually known to contain a large number of unusual minerals. Pegmatite is a very coarse-grained igneous rock. Simple pegmatites are composed of large crystals of ordinary minerals. (Jahns, 2007).

Chile is estimated to have the largest reserves by far (9.2 million tonnes), (U.S. Geological Survey, 2018). In Cornwall, England, the presence of brine rich in lithium was well known due to the region's historic mining industry, and private investors have conducted tests to investigate potential lithium extraction in this area (Bliss, 2021). The development of lithium ion batteries increased the demand for lithium and became the dominant use in 2007 (*"Minerals Yearbook, 2007"*). With the surge of lithium demand in batteries in the 2000s, new companies have expanded brine isolation efforts to meet the rising demand (Kogel, 2006). It has been argued that lithium will be one of the main objects of geopolitical competition in a world running on renewable energy and

dependent on batteries, but this perspective has also been criticised for underestimating the power of economic incentives for expanded production (Overland, 2019). However, the transition to clean energy is not as simple as replacing fossil fuels with renewable sources such as wind, solar and hydro. In order to power the clean energy revolution, we need a range of critical minerals that are essential for the generation, transmission and storage of energy. Critical minerals/elements are a big deal in this scenario and lithium commands a preeminent position, particularly due to its role in powering electric vehicles (EVs) and storing intermittent energy generated by renewable sources.

## **2. LITERATURE REVIEW ON LITHIUM-ION ENRICHMENT**

Lithium-ion enrichment covers both the geological processes that create natural lithium deposits and the technological methods for extracting and concentrating lithium-ions for use in batteries and potential nuclear applications. The focus of this paper is on technological methods for extracting and concentrating lithium-ions with particular attention to ores.

### **2.1. Geological Processes and Natural Enrichment**

Lithium is a highly incompatible element, meaning it does not fit easily into the crystal structures of common rock-forming minerals. This results in its concentration in the residual fluids during geological processes (Bowell, et al, 2020)

- **Magmatic Processes:** Lithium concentrations increase systematically in newly formed partial melts, ultimately leading to high concentrations in pegmatites and greisens (types of igneous rocks).
- **Brine and Geothermal Waters:** Weathering and other processes can leach lithium from rocks into aqueous solutions. Over time, in closed-basin salars (salt flats) and geothermal systems, natural evaporation processes lead to significant enrichment of  $\text{Li}^+$  ions to economically recoverable concentrations.

### **2.2. Extraction and Enrichment Technologies**

To meet the increasing demand for lithium, especially for lithium-ion batteries, various extraction and enrichment technologies have been developed from both primary (natural) and secondary (recycled) sources (Halkes et al.,2024).

- **Direct Lithium Extraction (DLE):** This is a key focus in recent literature for extracting lithium from low-concentration aqueous solutions like brines and seawater. Technologies reviewed include:
  - **Adsorption:** Using selective adsorbents to capture lithium ions.
  - **Membrane Separation:** Processes like forward osmosis and electrolysis using nanoporous membranes to separate and concentrate  $\text{Li}^+$  ions from other ions (e.g.,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ).
  - **Electrochemical Methods:** Utilizing redox reactions or electrochemical pumping with solid electrolytes to recover and enrich lithium with high selectivity and potential energy output.

**Recycling from Spent Batteries:** A significant body of literature addresses the recovery of lithium from used lithium-ion batteries to foster a circular economy (Lv et al, 2014):

- **Methods typically involve:**
  - **Pretreatment:** Processes like crushing and thermal treatment to liberate components.
  - **Leaching:** Using inorganic or organic acids to dissolve the cathode materials.

- Separation and Enrichment: Techniques like solvent extraction, precipitation, and electrolysis to isolate and enrich lithium from the resulting leach liquors.

### **2.3. Lithium Isotope Enrichment**

A separate but related topic in the literature is the enrichment of specific lithium isotopes, particularly  ${}^6\text{Li}$ , for applications in nuclear fusion reactors. This involves highly specialized chemical exchange or electrochemical processes with high separation factors.

## **3. SOURCES OF LITHIUM MINERALS IN NIGERIA**

Lithium deposits in Nigeria have been part of the land for millions of years, locked in pegmatites that formed during the Pan African geological shake up around 600 million years ago (Hassan, 2014). The Nigerian Geological Survey Agency has been mapping out high-grade lithium deposits across the country since 2018, identifying areas like Nasarawa's Keffi district and Kwara's southwest as rich in lithium. These areas contain pegmatite rocks initially thought to be limited to a pegmatite belt containing hundreds of pegmatite dykes and veins intruding basement complex rocks comprising quartz, mica, schist and granite gneisses. They are reported to be associated with tin and columbite-tantalite mineralization (Garba 2003; Okunlola 2005; Okunlola & Ocan, 2009) in (Umar, 2024). Okunlola (2005) in (Hassan, 2024) classified Nigeria's pegmatite belt into seven (7) broad fields namely: Nasarawa-Keffi, Ijero-Aramoko, Ibadan–Osogbo, Lema-Share, Oke-Ogun, Kabba-Isanlu and Kushaka-Birnin Gwari. Nigeria is rich in lithium deposits, with significant reserves found in several states, including Nasarawa, Kogi, Kwara, Ekiti, Oyo, Kaduna, Cross River, Bauchi, Niger, and the Federal Capital Territory. These deposits are scattered across a 450-mile belt, known as the "Lithium Belt," which stretches from the southwest corner of Nigeria to Kano in the north. Recent lithium ore exploitation across the country has widened the pegmatite belt to cover almost the entire Nigerian landmass underlain by basement complex (Figure 1). Lithium bearing pegmatites have been established to occur in many states including Nasarawa, Oyo, Osun, Ogun, Ekiti, Kogi, Kwara, Kebbi, FCT, Adamawa, Taraba, Cross River, Niger and Kaduna States (Hassan, 2024). The potential of Nigeria's lithium reserves is significant, with some pegmatites hitting grades as high as 13% lithium oxide, far above the global mining cut-off. This could position Nigeria as a key player in the global lithium supply chain, particularly as demand for the metal grows due to its use in electric vehicle batteries and other renewable energy technologies (Hassan, 2024).

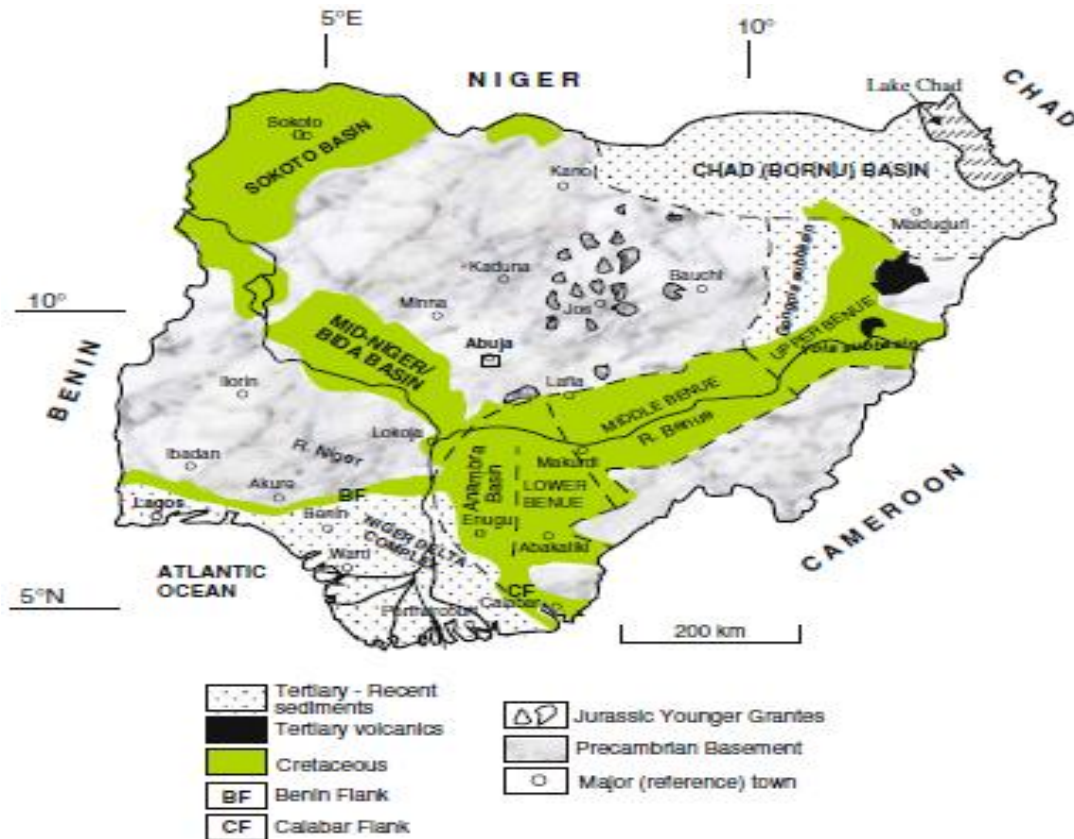


Figure 1: "Lithium Belt" Nigerian landmass underlain by basement complex

#### 4. METHODS OF LITHIUM EXTRACTION

Historically, two primary methods have dominated lithium extraction:

*Solar Evaporation from Brine:* Lithium-rich brine is pumped into vast evaporation ponds, where the sun concentrates lithium over 12–24 months and hard rock mining (An, 2012).

*Lithium Hard Rock Ores:* Lithium-bearing minerals like spodumene are extracted, crushed and chemically processed.

The main source of lithium at present in Nigeria is the hard rock ore of the metal. There are good number of minerals containing lithium, however, only four are actively mined for lithium production. These include: Spodumene, which is the most common by far. Therefore, this paper focuses primarily on spodumene, which is the major lithium mineral and commonly sold as-mined or processed.

#### 5. DEVELOPING LITHIUM ENRICHMENT FLOWSHEET

In order to develop a process flowsheet for Nigeria's lithium deposit to produce lithium ion, certain steps must be carried out: Selection of representative samples for testing and sample preparation; analysis of the ore to determine its mineralogy, texture and chemical composition; laboratory testing to determine the lithium ore's response to various processing conditions; and finally the flowsheet design. Additionally, iterative process (starting from conceptual flowsheet) should be carried out to refine the flowsheet as needed. It is also necessary to use industry standards and best practices to ensure the flowsheet meets industry standards and incorporate such best practices in the flowsheet.

## **5.1 Steps to developing Nigerian Lithium Ore Enrichment Flowsheet**

Developing a flowsheet for mineral processing and metal extraction involves several steps:

- Selection of representative samples for testing and sample preparation;
- *Ore characterization*: Understanding the mineralogical and chemical composition of the ore. Analysis of the ore to determine its mineralogy, texture and chemical composition;
- *Process selection*: Selecting the most suitable processes for mineral processing and metal extraction based on the ore characteristics. This means laboratory testing to determine the lithium ore's response to various processing conditions especially with regard to flotation process;
- *Flowsheet design*: Designing the flowsheet, including the sequence of unit operations and the connections between them. Additionally, iterative process (starting from conceptual flowsheet) should be carried out to refine the flowsheet as needed.
- *Mass balance*: Calculating the mass balance of the flowsheet to ensure that the inputs and outputs are balanced.
- *Economic evaluation*: Evaluating the economic viability of the flowsheet.
- *Laboratory and pilot-scale testing*: Laboratory and pilot-scale testing are essential for validating the flowsheet and optimizing process conditions.
- *Flowsheet optimization*: Flowsheet optimization involves identifying opportunities to improve metal recovery, reduce costs, and minimize environmental impacts.
- It is also necessary to use industry standards and best practices to ensure the flowsheet meets industry standards and incorporate such best practices in the flowsheet.

## **5.2 Key Considerations**

Nigerian lithium ores are often associated with several minerals and elements, including:

- Tantalum (Ta) and Niobium (Nb): These minerals are commonly found alongside lithium in pegmatite deposits, particularly in states like Kogi, Nasarawa and Kwara.
- Tin (Sn): Tin is another mineral often associated with lithium in Nigerian pegmatites, particularly in the Jos Plateau region.
- Beryllium (Be): Beryllium is a rare mineral found in some Nigerian lithium deposits, particularly in the Nasarawa and Kogi states.
- Cesium (Cs): Cesium is a rare alkali metal often associated with lithium in Nigerian pegmatites.
- Silica (SiO<sub>2</sub>) and Alumina (Al<sub>2</sub>O<sub>3</sub>): These minerals are common gangue minerals found in Nigerian lithium ores.
- Rare Earth Elements (REEs): Some Nigerian lithium deposits, particularly in the Sokoto Sedimentary Basin, contain REEs like neodymium (Nd) and dysprosium (Dy).

These associated minerals can impact the processing and extraction of lithium, and their presence may require specialized processing techniques.

- 5.2.1 These are very important in the development of the flowsheet. Ore type and mineralogy. Understanding the associated elements present in lithium ores is crucial for optimizing processing conditions and achieving economic extraction. In terms of the elements often associated with lithium minerals, the following are very important in the development of the flowsheet and overall processing of lithium ores: Aluminium (Al), Silicon (Si), Iron (Fe), Manganese (Mn), Magnesium (Mg), Calcium (Ca), Sodium (Na), Potassium (K), Rubidium (Rb), Cesium (Cs), Tantalum (Ta), Niobium (Nb), Tin (Sn), Tungsten (W) and

Molybdenum (Mo). The type of ore and its mineralogy play a crucial role in determining the flowsheet, see Table 1. These elements may be present in varying amounts and can impact the processing and extraction of lithium. Some associated elements, like tantalum and niobium, can be valuable by-products, while others, like iron and silicon, may need to be removed to produce high-purity lithium. The associated minerals/elements can also affect the mineralogy and chemistry of the ore, influencing the choice of processing methods and the efficiency of lithium extraction.

- 5.2.2 *Metal recovery*: The flowsheet should be designed to maximize metal recovery while minimizing costs.
- 5.2.3 *Environmental considerations*: The flowsheet should be designed to minimize environmental impacts.
- 5.2.4 *Scalability*: The flowsheet should be scalable to accommodate changes in ore throughput or grade.

**Table 1.** Possible associated minerals with Nigerian lithium ores

Mineral	Formula
Coltan (Columbite-Tantalite)	(Mn,Fe)(Ta,Nb) <sub>2</sub> O <sub>6</sub>
Columbite	(Mn,Fe)Ta <sub>2</sub> O <sub>6</sub>
Tantalite	(Fe,Mn)Ta <sub>2</sub> O <sub>6</sub>
Quartz	(SiO <sub>2</sub> )
Feldspar	(KAlSi <sub>3</sub> O <sub>8</sub> – NaAlSi <sub>3</sub> O <sub>8</sub> – CaAlSi <sub>3</sub> O <sub>8</sub> )
Mica	(K <sub>2</sub> Al <sub>4</sub> (Al <sub>2</sub> Si <sub>6</sub> O <sub>20</sub> (OH) <sub>4</sub> )
Amphibole (Hornblende)	Ca <sub>2</sub> (Mg,Fe,Al) <sub>5</sub> Si <sub>6</sub> Al <sub>2</sub> O <sub>22</sub> (OH) <sub>2</sub>
Pyroxene (Diopside)	(MgCaSi <sub>2</sub> O <sub>6</sub> )
Apatite	(Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> (F,Cl,OH)
Zircon	(ZrSiO <sub>4</sub> )
Cassiterite	(SnO <sub>2</sub> )
Wolframite	((Fe,Mn)WO <sub>4</sub> )
Bismuthinite	(Bi <sub>2</sub> S <sub>3</sub> )
Pyrite	(FeS <sub>2</sub> )
Galena	(PbS)
Olivine	(Mg,Fe) <sub>2</sub> SiO <sub>4</sub>
Garnet (Almandine)	(Fe <sub>3</sub> Al <sub>2</sub> (SiO <sub>4</sub> ) <sub>3</sub> )
Tourmaline	(Na,Mg,Al,Li,B) <sub>3</sub> Al <sub>6</sub> (BO <sub>3</sub> ) <sub>3</sub> Si <sub>6</sub> O <sub>18</sub> (OH) <sub>4</sub>

## 6. PRIMARY PROCESSING: LITHIUM ORE TO LITHIUM CONCENTRATE

Mineral processing is necessary to make raw ores profitable and technologically feasible by separating valuable minerals from waste rock (gangue). In this case, this concentration process is crucial because lithium ores contain only a low percentage of the lithium element and is uneconomical to refine directly. Mineral processing of the lithium ore creates a more concentrated material for further refining, which reduces transportation costs and improves the efficiency of downstream processes.

- Primary processing consists mainly comminution and concentration of the run-of-mine ore.
- Comminution is the *liberation* of the valuable mineral by breaking the lithium ore so that the individual mineral components of the ore become independent of each other.
- Concentration process usually adopted in lithium beneficiation is flotation technique to separate the lithium mineral from the gangue to produce an enriched portion of the lithium mineral in relation to the feed.

## 6.1 Flotation Technique

Flotation is a mineral processing technique used to separate valuable minerals from waste rock by altering the surface properties of the minerals and it is one of the most important techniques used in the concentration of lithium ion.

- Flotation technique involves creating a pulp of the comminuted ore and water, and then adding surfactants (collectors) that bind to the lithium minerals, making them hydrophobic (water-repelling).
- The mixture is then agitated and air is introduced, creating bubbles to which the lithium mineral particles are attached, causing them to float to the surface, where they are skimmed off as lithium mineral concentrate.
- Flotation is a complex process and optimizing the various factors can be challenging. However, it remains the most widely used and effective technique in the processing of lithium ore containing spodumene.

The factors which may affect the lithium mineral flotation include:

*Grind size:* Very fine particle sizes can facilitate the liberation and separation of the lithium mineral, spodumene from its associated gangue minerals;

*pH:* Affects the activity of collectors and the flotation process as a system;

*Collector type:* Different collectors are used for different minerals, oleic acid for oxides for example;

*Frother type:* Affects the froth stability and mineral carrying capacity;

*Temperature:* Affects the flotation kinetics and mineral behaviour;

*Reagent dosage:* Affects the flotation performance and cost.

**Table 2.** Reagents for Lithium mineral Flotation

Class of reagents	Examples of reagents
Collectors	Oleic acid, Sodium oleate, Sodium lauryl sulphate, Fatty acids (e.g., stearic acid, palmitic acid)
Frothers	Methyl isobutyl carbinol (MIBC), Ethanol, Glycols (e.g., ethylene glycol, propylene glycol)
pH modifiers	Sodium hydroxide (NaOH), Hydrochloric acid (HCl), Sodium carbonate (Na <sub>2</sub> CO <sub>3</sub> )
Activators	Sodium sulphide (Na <sub>2</sub> S), Sodium metabisulphite (Na <sub>2</sub> S <sub>2</sub> O <sub>5</sub> )
Depressants	Sodium cyanide (NaCN), Sodium silicate (Na <sub>2</sub> SiO <sub>3</sub> )
Flocculants	Polyacrylamide, Polyethylene oxide
Surfactants	(e.g., alkyl sulphonates, alkyl ethoxysulphates)
Polymers	(e.g., polyacrylic acid, polymethacrylic acid)
Inorganic salts	(e.g., sodium chloride, calcium chloride)

It is important to note that the type and dosage of reagents used in the Nigerian lithium mineral flotation may vary depending on the specific requirements of the operation and the characteristics of the lithium ore being processed.

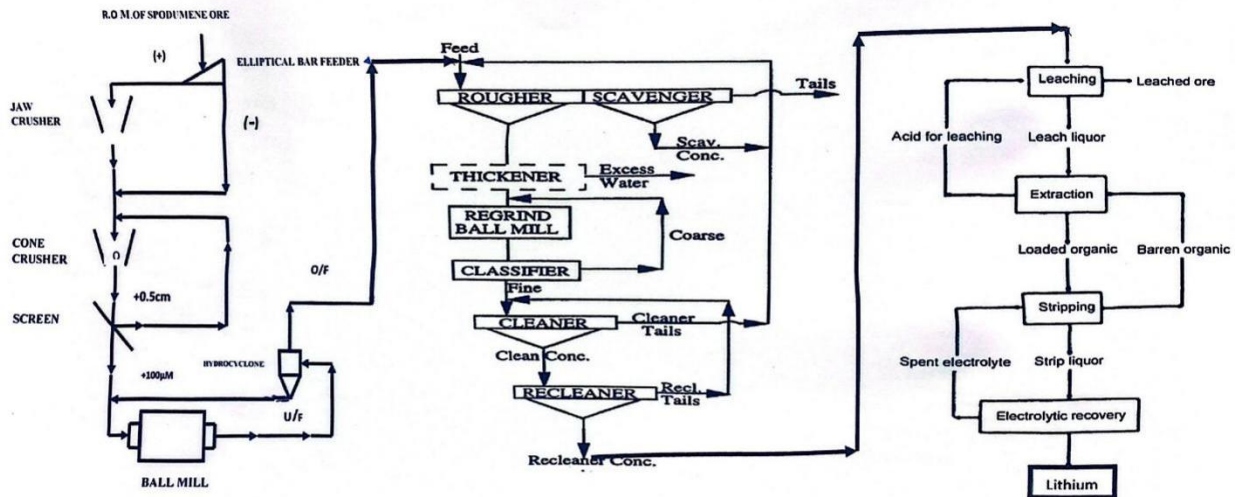
## 6.2 Secondary processing: Conversion or extraction of the metal Li<sup>+</sup> from the lithium concentrate

Lithium compounds are produced in a variety of forms including lithium carbonate (Li<sub>2</sub>CO<sub>3</sub>), lithium oxide (Li<sub>2</sub>O), and lithium hydroxide (LiOH). Conventional and common lithium metal extraction has typically involved acid or alkaline leaching of lithium-containing ores (spodumene) is used to dissolve the lithium from the spodumene concentrate, followed by extraction of the

metal, concentration of the lithium solution and then conversion to lithium carbonate or lithium hydroxide using electrolytic process.

- The extraction process typically involves the following steps, the first two being subsidiary steps that lead to leaching process
- *Calcination*: The spodumene concentrate from primary processing is calcined to high temperatures (around 1100°C) to convert the spodumene into a more reactive form (alpha form to beta form)
- *Acid roasting*: The calcined ore is mixed with acid (usually sulphuric acid) and roasted at high temperatures (around 250°C) to break down the spodumene and release lithium.
- *Leaching*: The resulting material is mixed with water to form slurry and subjected to leaching, which allows the lithium to dissolve into the solution.
  - *Precipitation*: The lithium-rich solution is then treated with a precipitating agent (such as sodium carbonate) to precipitate or strip out the lithium as lithium carbonate ( $\text{Li}_2\text{CO}_3$ ) or in some cases lithium hydroxide ( $\text{LiOH}$ ), depending on the precipitating agent used.
  - *Electrolysis*: The concentrated solution is then subjected to electrolysis, where electric current is passed through the solution, causing the lithium ions to be reduced to lithium metal.
  - *Refining*: The resulting lithium metal is then refined and purified through various processes, such as distillation or zone refining.
- All the above processes are summarized in the flowsheet. As explained above, the flowsheet is just a graphical representation of the major stages in the conversion of the ore to the metal. Some details cannot be included because of space but further details can be obtained from the author or other professionals.

### FLWSHEET FOR THE ENRICHMENT OF LITHIUM ION FROM NIGERIAN LITHIUM ORES



## 7. CONCLUSION

The enrichment or extraction of lithium ion from run-of-mine ore can be described as of two major stages viz. primary processing and secondary processing. The processes require careful control of conditions to achieve high recovery of the lithium mineral in the concentrate and meticulous control of the conditions to produce high purity of the lithium ion or metal. The other major technique used in the beneficiation of lithium minerals is dense medium separation (DMS). Dense

media separation is usually employed for coarse gangue rejection, but can also be used to produce lithium concentrates from high grade ores. Magnetic separation technique can also be employed to separate magnetite or other forms of the mineral after roasting the concentrate. Still, froth flotation is the most popular technique because of the fine particle size feed and high recovery it offers. Spodumene from pegmatite deposits is expected to be the main source of lithium from ores in Nigeria at present although future sources would most probably include other minerals such as lepidolite, petalite, zinnwaldite, jadarite and hectorite. By developing the flowsheet, there are both technical and economic benefits that accrue to any investor in the exploitation of lithium in Nigeria. These include improved process control which can help to identify key variables and optimizing process conditions. The flowsheet would no doubt help reduce downtime, if it is well-designed, by identifying potential issues and optimizing maintenance schedules, identify potential safety hazards and optimize process conditions to minimize risks. Succinctly, by developing a flowsheet for the lithium ion ( $\text{Li}^+$ ) from Nigerian ores, mining investors will optimize their lithium ore processing and lithium ion ( $\text{Li}^+$ ) extraction operations, leading to improved efficiency, reduced costs and increased profitability.

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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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## BIOMASS RESOURCE ASSESSMENT USING THE INVENTORY APPROACH FOR BIOFUEL PRODUCTION POTENTIAL IN EDO STATE, NIGERIA

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### ABSTRACT

*Biomass resources present a vast, untapped potential for sustainable energy production in Nigeria. This study uses an inventory approach to evaluate the availability and suitability of biomass resources in Edo State for biofuel production. It identifies the types, quantities, and spatial distribution of biomass resources, focusing on agricultural, forest, urban, and other wastes. Solid biomass and waste constitute about 80% of Nigeria's total primary energy consumption. The research assesses biomass feedstocks for first to fourth-generation biofuels, exploring their viability for bioethanol, biodiesel, and biogas production. Emerging biofuel projects in Nigeria predominantly depend on first-generation feedstocks, primarily food crops, which could create conflicts between food and energy needs. This study highlights the importance of shifting focus to non-food biomass resources, including agricultural residues and organic waste. Preliminary findings reveal that Edo State possesses significant potential for biofuel production, supported by favorable agro-ecological conditions and extensive crop cultivation. However, challenges such as insufficient infrastructure, limited access to modern agricultural technologies, and policy gaps hinder progress. The study provides crucial insights for policymakers, researchers, and investors, emphasizing the sustainable utilization of biomass resources for renewable energy production. Addressing identified challenges could unlock the Edo State's biomass potential, enhancing energy diversification and contributing to sustainable development. The results aim to guide optimized biomass resource utilization, promoting biofuel as a viable solution for Nigeria's energy and environmental challenges.*

## **1. INTRODUCTION**

The combustion of fossil fuels, including coal, oil, and natural gas, has dominated global energy production for decades (Andres et al., 2012). The use of fossil fuels as primary energy is a major global concern due to its substantial contribution to greenhouse gas (GHG) emissions, particularly carbon dioxide (CO<sub>2</sub>), which is a leading driver of climate change. The release of CO<sub>2</sub> during fossil fuel combustion exacerbates global warming, resulting in severe environmental impacts. Fossil fuels contribute approximately 23% of global CO<sub>2</sub> emissions (Saboori et al., 2013), emphasizing the urgent necessity for transitioning to cleaner energy sources to meet international climate goals, such as those outlined in the Paris Agreement.

While Sub-Saharan Africa contributes less than 4% of global CO<sub>2</sub> emissions (IRENA, 2023), the region faces disproportionate risks from climate change. Rising temperatures, erratic rainfall, desertification, and extreme weather events threaten livelihoods dependent on agriculture and natural resource extraction (IPCC, 2023; Climate Analytics, 2024; IMF, 2024). Nigeria, as Africa's largest economy, exemplifies the challenges of balancing economic growth with environmental sustainability. Fossil fuels dominate the country's energy mix, accounting for over 80% of energy production and approximately 59.5% of total CO<sub>2</sub> emissions (Tajudeen et al., 2015). With rapid population growth, urbanization, and industrialization, Nigeria faces mounting environmental challenges, including rising GHG emissions, deforestation, and pollution.

The Federal Republic of Nigerian has recently pledged to achieve net-zero emissions by 2060, necessitating a transition to renewable energy sources. Among these, biomass stands out as a promising alternative. Derived from organic materials such as agricultural residues, forestry by-products, and municipal waste, biomass offers a sustainable pathway for producing electricity, heat, and biofuels like biodiesel, bioethanol, and biogas (Fan et al., 2021; Kumar et al., 2023).

The global energy crisis and climate change emphasize the need to transition away from fossil fuels. Sustainable energy solutions are required to reduce environmental damage while improving energy security and fostering economic growth (IPCC, 2021). Among renewable energy options, biomass stands out as a promising alternative. Biomass, derived from agricultural residues, forestry by-products, and municipal waste, provides a sustainable way to generate electricity, heat, and biofuels such as bioethanol, biodiesel, and biogas (López et al., 2020; Balat, 2011). Biomass can reduce CO<sub>2</sub> emissions, enhance energy security, and diversify the energy mix (Chen et al., 2020) and fosters rural economic development.

Despite its potential, there are significant challenges in fully utilizing biomass in Sub-Saharan Africa. One of the key barriers is the lack of comprehensive biomass inventories that assess the availability and types of biomass resources. Effective biomass utilization depends on resource assessments that measure the quantity and quality of available biomass. Currently, biomass resource assessments use two main approaches: the inventory approach, which estimates physical quantities, and the economic approach, which considers price factors. However, the absence of international standards complicates the development of standardized data, hindering biomass optimization.

Improving biomass characterization and resource assessment techniques is crucial for enhancing biomass conversion technologies and ensuring efficient utilization. Accurate biomass inventories

are essential for informing policy decisions and guiding investments in bioenergy infrastructure. Moreover, better inventory systems are needed to explore the full potential of biofuels like bioethanol, biodiesel, and biogas, which remain underdeveloped in many African countries (Demirbas, 2009).

Biomass offers significant potential for renewable energy production and environmental sustainability. By focusing on detailed biomass resource inventories, Nigeria and Sub-Saharan Africa can unlock the potential of biofuels, contributing to energy transition goals. Biomass from agricultural residues, forestry by-products, and organic waste can replace fossil fuels, addressing energy poverty in rural areas, promoting economic development, and reducing environmental degradation. Investing in cleaner energy technologies and optimizing biomass utilization will foster sustainable growth, improve energy security, and support global climate goals.

The aim of this study is to assess the biomass resources available in Edo State, Nigeria, and evaluate their potential for biofuel production, with a focus on bioethanol, biodiesel, and biogas. The study aims to identify and explore the feasibility of utilizing first, second, third, and fourth-generation biomass feedstock, including agricultural residues, energy crops, and organic waste. It seeks to examine the opportunities for integrating non-food biomass resources into existing petroleum refinery infrastructure to co-process biofuels, thereby addressing the food-versus-fuel conflict. Additionally, the study aims to evaluate the current biomass conversion technologies in Nigeria, assess their readiness for large-scale application, and provide actionable insights for policymakers, researchers, and investors to foster sustainable bioenergy development in Edo State and contribute to Nigeria's energy security, sustainable agricultural practices, and greenhouse gas emission reduction goals.

## **2. LITERATURE SURVEY**

Energy plays a pivotal role in national development and economic expansion, and its significance cannot be overstated. Human progress, economic growth, and societal well-being rely heavily on the adequate, secure, and efficient provision of energy Abdallah et al., (2015). According to Lior (2011), patterns of energy use are closely linked to environmental quality and to essential resources such as water and food. In a related argument, Lior (2011) emphasized that Africa's energy sector requires urgent attention and strategic development to enhance citizens' quality of life and potentially supply energy to the global market.

The ongoing global energy crisis, compounded by the escalating threat of climate change, has intensified the need to shift away from heavy dependence on fossil fuels. Without alternative energy sources, shortages will persist and environmental degradation will worsen. Renewable and sustainable energy options—such as wind, solar, biomass, hydropower, ocean energy, and geothermal—are therefore being actively explored, each with distinct advantages and limitations. Abolhosseini et al. (2014) identified energy security, economic benefits, and reductions in carbon emissions as the principal drivers behind growing interest in renewable energy technologies.

Developing nations appear particularly vulnerable to the global energy crisis. Their economies are highly sensitive to fluctuations in energy markets due to excessive dependence on non-renewable energy sources and limited capacity to maintain stable and affordable energy supplies Hussain et al. (2019). Yet many developing countries, including Nigeria, possess abundant and largely untapped renewable resources with significant potential applications (Ismail et al., 2014; Orisaleye et

al., 2018; Ismail et al., 2013; Orisaleye et al., 2018). As noted by Piebalgs (2007), these countries are well positioned to expand renewable energy use given their ample resources—ranging from wind and solar to biomass, geothermal, and hydropower—although political and financial support may be required. Evidence further shows that renewable energy contributes positively to economic development and employment generation and supports environmental sustainability while enhancing energy self-sufficiency ((Osiolo et al., 2016; Tun et al, 2019).

Evans et al. (2009) evaluated the social impacts of renewable energy systems and ranked them using sustainability indicators. Their findings placed wind energy as the most sustainable option, followed by hydropower, solar photovoltaics, and geothermal. Mas'ud et al (2015), in assessing renewable energy readiness in Nigeria and Cameroon, reported high solar radiation levels and viable wind speeds in both countries. They also highlighted Africa's substantial energy potential, which could stimulate economic growth and meet future electricity demand. However, Ajayi (2009) observed that the diffusion of renewable technologies is hindered by challenges such as limited awareness and inadequate technical capacity.

Many developing nations—particularly in sub-Saharan Africa—possess vast arable land and rely heavily on agriculture, making biomass an abundant energy source. However, biomass is often used in inefficient or environmentally damaging ways. Despite these drawbacks, biomass still accounts for roughly 70% of total energy consumption in some countries Keles et al (2017). Keles et al (2017) estimate that by 2030 approximately 823 million Africans will depend on biomass for cooking and heating. In response, Gujba et al (2015) recommend prioritising the deployment of advanced cookstoves to mitigate indoor air pollution and relieve pressure on biomass supplies.

Global concern over climate change has led the United Nations to convene numerous conferences and summits focused on climate mitigation. These events have yielded major international agreements on greenhouse gas reduction. The Kyoto Protocol of 1997 (COP3) formally acknowledged anthropogenic CO<sub>2</sub> emissions as a key contributor to global warming and established differentiated responsibilities for emissions reduction based on countries' capacities and levels of development Gribb et al (2004). The Paris Agreement adopted at COP21 in 2015 set the strategic direction for post-2020 climate action, recognizing the need to achieve net-zero emissions by 2050 to constrain global warming to 1.5 °C—a threshold considered socially and economically safer Summit (2019). Subsequent meetings, such as COP25 in Madrid (2019), sought to clarify operative rules for the Paris Agreement and encouraged nations to submit strengthened climate action plans despite disagreements over certain implementation mechanisms (KPMG, 2019).

Abolhosseini et al. (2014) argue that the two most effective approaches to lowering CO<sub>2</sub> emissions and mitigating climate change are large-scale replacement of fossil fuels with renewable energy and significant improvements in energy efficiency. Nevertheless, Keles et al (2017) caution that robust and reliable data remain insufficient for effective biomass energy planning or policy formulation. As such, proper management and sustainable utilization of biomass resources are essential to maximize their role in energy production.

Against this background, the present study identifies viable biomass resources available in Nigeria and evaluates the technologies suitable for their conversion into bioenergy. It further estimates both the theoretical and technical potentials of these resources and reviews existing Nigerian policy measures aimed at promoting biomass-based energy development.



samples, including crop residues like maize stalks, rice husks, and cassava peels, were carefully collected and cataloged. Forestry by-products such as sawdust and wood offcuts were sourced from logging and sawmill operations, while organic waste was gathered from municipal dumpsites and composting facilities. Detailed documentation was maintained, including the source, quantity, and condition of biomass.

### **3.3 Interviews**

Structured interviews were conducted with key stakeholders, including farmers, forestry operators, municipal officials, and industry stakeholders, to gather qualitative and quantitative data on biomass availability and utilization. Farmers were interviewed to estimate the volume of crop residues produced and understand current practices for disposal or reuse, such as burning, composting, or feeding to livestock. Forestry operators provided insights into the types and quantities of residues generated from logging and sawmill activities. Municipal officials were consulted to assess the volume of organic waste collected, collection rates, and waste management practices in urban and peri-urban areas. Industry stakeholders, such as bioenergy companies and agricultural cooperatives, were engaged to explore existing biomass supply chains and demand for feedstocks. Interviews followed a structured format, starting with background questions about the respondent's operations, followed by in-depth questions on biomass generation, current usage practices, and barriers to efficient utilization. The interview data were cross verified with field observations and secondary sources to ensure consistency and reliability.

### **3.4 Direct Measurements**

Direct measurements were performed to quantify biomass feedstocks and evaluate their potential for biofuel production using standardized sampling and analytical techniques. For agricultural residues, a representative portion of the collected material was weighed in its fresh state, then air-dried to a constant weight to determine dry matter content. Wood residues, including sawdust and wood chips, were measured volumetrically, and samples were analyzed to determine their moisture content. Municipal organic waste was sorted to separate biodegradable components, which were weighed and characterized to assess their suitability for biofuel production. Proximate analysis was conducted on all biomass samples to determine key properties such as moisture content, ash content, volatile matter, and fixed carbon using standard laboratory equipment like muffle furnaces. Additionally, the calorific value of the biomass was measured using a bomb calorimeter to estimate its energy potential. Bulk density measurements were conducted to evaluate the logistical feasibility of storage and transportation. All measurements followed international standards such as ASTM D1762, ensuring accuracy and comparability of results. Samples were appropriately labeled and stored to prevent contamination or degradation before analysis.

## **4. RESULTS**

The biomass resource inventory conducted in Edo State revealed significant potential for biofuel production from a variety of biomass feedstocks, including agricultural, forest, urban, and other organic wastes. Edo State's agro-ecological zones, comprising the Rainforest, Derived Savanna, Freshwater Swamp, and Floodplain zones, offer a diverse range of climatic and soil conditions that support the cultivation of various crops such as oil palm, cassava, rice, and maize, while also enabling sustainable agricultural practices and biodiversity conservation.

#### **4.1 Agro-Ecological Zones of Edo State**

The state's agro-ecology is defined by varying climatic and vegetative zones that influence the types of crops grown, the productivity of its land, and the agricultural practices employed. These agro-ecological zones are crucial in understanding the potential for biomass resource development and biofuel production, as the state's diverse climatic conditions provide a wide range of possibilities for cultivating various biomass feedstocks. The State spans across different climatic zones, from the humid tropical zones in the south to areas with relatively moderate rainfall in the north (Table 1). These variations in climate, rainfall patterns, and temperature influence the vegetation types, and subsequently, the types of crops that can thrive in different parts of the state. Edo State has three primary climatic zones: the Humid Tropical Zone in the south, characterized by high rainfall (2000-3000 mm) suitable for cash crops like cocoa, cassava, and oil palm; the Sub-Humid Zone in the central and northern regions, with moderate rainfall (1,200-2000 mm) ideal for crops such as maize, rice, and energy crops like sweet sorghum; and the Forest-Savannah Transition Zone, where forest and savannah vegetation overlap, supporting a variety of crops including tropical fruits, shrubs, and grasses for livestock grazing. These zones provide diverse agricultural opportunities, particularly for biofuel production.

##### *4.1.1 Biomass Resource Inventory in Edo State*

Edo State's diverse agro-ecological zones play a crucial role in determining the types of crops cultivated and the availability of biomass resources. These resources serve as key feedstocks for biofuel production, offering immense potential to bolster the state's renewable energy sector. This inventory examines the biomass feedstocks available across the agro-ecological zones, including agricultural biomass, energy crops, forestry by-products, and urban biomass, highlighting their contributions to Edo State's bioenergy potential (Tables 2, 3, 4, and 5).

The rich agricultural diversity, with energy crops such as oil palm, cassava, sugarcane, maize, plantain, groundnut (peanut), soybean, and *Jatropha* are widely cultivated across its zones. These crops form an integral part of the production of bioethanol, biodiesel, and biogas, underscoring their importance in enhancing the state's renewable energy capabilities. Fertile soils and favorable climatic conditions (Table 1) support the large-scale cultivation of these high-yield crops, making agricultural biomass a cornerstone of Edo State's biofuel potential.

Edo State also benefits significantly from its extensive forest resources, particularly within the forest-savannah transition zone. This area provides a vast, untapped reservoir of biomass, including wood, sawdust, and other forestry by-products, which are suitable for renewable energy production. These resources enhance the state's capacity to generate bioenergy and reduce dependence on fossil fuels, presenting opportunities for large-scale and sustainable biofuel production.

The growing urban centres of Edo State generate considerable amounts of organic waste, such as food waste, yard waste, and municipal solid waste (MSW). This urban biomass represents a substantial resource for biofuel production via anaerobic digestion, a process that converts organic material into biogas. By establishing waste-to-energy facilities in urban areas, Edo State can address waste management challenges while simultaneously producing renewable energy for applications such as cooking, electricity, and heating. This dual-purpose approach promotes environmental sustainability and energy self-reliance.

**Table 1.** Summarizing The Agro-Ecological Zones of Edo State

Agro-Ecological Zone	Description	Location	Characteristics	Agricultural Activities	Soil Type	Economic Significance
Rainforest Zone	Dense vegetation, high rainfall, and biodiversity.	Southern and central parts of the state	<ul style="list-style-type: none"> <li>- High annual rainfall (2000–3000 mm)</li> <li>- Humid climate, well-drained soils</li> </ul>	<ul style="list-style-type: none"> <li>- Crops: Cocoa, rubber, oil palm, yam, cassava, plantain, maize</li> <li>- Livestock: Small-scale poultry, goat, sheep farming</li> </ul>	<ul style="list-style-type: none"> <li>- Deep, well-drained soils</li> <li>- Rich in organic matter</li> </ul>	<ul style="list-style-type: none"> <li>- Plantation agriculture (cash crops)</li> <li>- Forest conservation</li> </ul>
Derived Savanna Zone	Transitional zone with a mix of forest and grassland vegetation.	Northern parts of the state	<ul style="list-style-type: none"> <li>- Transitional vegetation</li> <li>- Moderate rainfall (1200–2000 mm)</li> <li>- Grassland with scattered trees</li> </ul>	<ul style="list-style-type: none"> <li>- Crops: Maize, yam, cassava, guinea corn, millet, cowpea</li> <li>- Livestock: Cattle rearing, poultry farming</li> </ul>	<ul style="list-style-type: none"> <li>- Loamy to sandy soils</li> <li>- Moderate fertility</li> </ul>	<ul style="list-style-type: none"> <li>- Suited for mechanized and large-scale farming</li> <li>- Agro-industrial potential</li> </ul>
Freshwater Swamp Zone	Low-lying areas prone to waterlogging, close to rivers and wetlands.	Along floodplains of rivers (e.g., Niger)	<ul style="list-style-type: none"> <li>- High rainfall (2000–2500 mm)</li> <li>- High humidity - Periodic flooding</li> <li>- Waterlogged soils rich in organic matter</li> <li>- Vegetation: Mangroves, swamp forests</li> </ul>	<ul style="list-style-type: none"> <li>- Crops: Rice, sugarcane, vegetables</li> <li>- Fisheries: Aquaculture, artisanal fishing</li> </ul>	<ul style="list-style-type: none"> <li>- Waterlogged soils</li> <li>- Acidic and peaty soils</li> </ul>	<ul style="list-style-type: none"> <li>- Supports flood-tolerant crop farming</li> <li>- Key area for fisheries and biodiversity conservation</li> </ul>
Mangrove Forest Zone	Riverine areas, characterized by periodic flooding and rich alluvial deposits.	Southernmost areas (coastal/estuarine regions)	<ul style="list-style-type: none"> <li>- Seasonal flooding</li> <li>- Moderate to high rainfall - Brackish water ecosystem</li> <li>- High humidity</li> <li>- Saline soils</li> </ul>	<ul style="list-style-type: none"> <li>- Limited farming due to salinity</li> <li>- Fisheries: Shrimp and fish farming</li> </ul>	<ul style="list-style-type: none"> <li>- Alluvial soils</li> <li>- High fertility</li> </ul>	<ul style="list-style-type: none"> <li>- Crucial for fisheries and ecological balance</li> <li>- Potential for eco-tourism and mangrove restoration</li> </ul>

Agricultural residues (Table 4) further augment Edo State's biomass resource inventory. Key crops like oil palm, cassava, maize, pineapples, rice, plantain, and groundnut yield significant amounts of residues, including fronds, peels, husks, and stalks. Annually, these residues amount to approximately 1–1.5 million tons, presenting opportunities for diverse applications such as biomass energy production, biogas generation, and the creation of organic fertilizers. However, realizing the full potential of these resources requires addressing challenges such as inefficient collection systems, inadequate infrastructure, and post-harvest losses. Overcoming these barriers will enable Edo State to maximize its renewable energy potential while contributing to sustainable waste management and recycling initiatives.

#### *4.1.2 Inventory of Aquatic Weeds for Biofuels Production in Edo State*

The study on aquatic weeds for biofuels production in Edo State reveals significant biomass availability across different regions, highlighting their potential for renewable energy generation (Table 6). The Benin River Basin, with over 12,000 tons of water hyacinth annually, represents the highest biomass density, capable of producing up to 1,500 cubic meters of methane per ton of dry biomass through biogas conversion. The Esan Region, characterized by duckweed and cattails, contributes about 8,000 tons of biomass annually, with a bioethanol yield of estimated values of 400 liters per ton. In Orhionmwon wetlands, approximately 6,000 tons of reeds and cattails are available for bioethanol and biochar production. Coastal areas in Ovia North support algae with 25-30% lipid content, offering a biodiesel output of about 2,000 liters per ton. Collectively, Edo State may generate approximately 26,000 tons of aquatic weed biomass annually, suitable for producing 10,000 cubic meters of biogas, 10,400 liters of bioethanol, and 5,200 liters of biodiesel. These findings demonstrate the potential of aquatic weeds to contribute to energy diversification and environmental sustainability in Edo State.

#### *4.1.3 Animal Waste for Biofuels Production in Edo State*

Animal waste in Edo State holds significant potential for biofuels production, with cattle manure alone contributing around 600,000 tons annually, which can produce up to 10,000 cubic meters of biogas. Poultry waste, amounting to approximately 150,000 tons per year, is suitable for biogas production, while pig manure, with an annual output of 100,000 tons, can also be used for biogas and composting. Additionally, goat and sheep manure, estimated at 50,000 tons annually, provides a further source for biogas production and organic fertilizer. Animal fats, especially from pigs and cattle, can be converted into biodiesel, with an estimated output of up to 5,000 liters per year. Despite the high potential, challenges such as inefficient collection, transportation, and processing infrastructure remain. To address these, solutions like developing centralized biogas plants near livestock farms, establishing proper waste collection and storage systems, and promoting small-scale biogas plants and biodiesel production facilities are crucial. Proper management of animal waste not only provides renewable energy but also helps in waste reduction and improved agricultural practices in the region.

**Table 2.** Energy Crops Commonly Cultivated in Edo State

Energy Crop	Description	Agro-Ecological Zone	Uses	Economic Significance
Oil Palm	Perennial crops yielding palm oil and kernel oil. Grows well in humid conditions.	Rainforest Zone	- Biofuel production (biodiesel) - Edible oil - Industrial applications	- Major cash crop - Supports biofuel industry and export
Cassava	Root crop with high starch content. Thrives in diverse conditions.	Rainforest and Derived Savanna Zones	- Ethanol production - Livestock feed - Food products	- Staple food crop - Source of income for smallholder farmers
Sugarcane	Tall perennial grass rich in sugar. Prefers waterlogged soils.	Freshwater Swamp Zone	- Bioethanol production - Sugar production	- Potential for renewable energy projects - Industrial sugar and ethanol production
Maize	Versatile cereal crop. Grows well in moderate rainfall areas.	Derived Savanna and Rainforest Zones	- Bioethanol production - Livestock feed - Food products	- Key to food security - Input for biofuel and livestock industries
Jatropha	Drought-resistant shrub with seeds rich in oil.	Derived Savanna Zone	- Biodiesel production - Medicinal uses	- Potential to enhance rural economy - Sustainable biofuel source
Plantain/Banana	High-yielding fruit crops suited to humid conditions.	Rainforest Zone	- Bioethanol production - Food products	- Food security crop - Adds value in biofuel production
Rice	Staple grain crop requiring waterlogged conditions.	Freshwater Swamp Zone	- Bioethanol production - Food products	- Supports rural livelihoods - Input for renewable energy projects
Groundnut (Peanut)	Legume rich in oil content. Grows in moderately dry conditions.	Derived Savanna Zone	- Biofuel production - Edible oil and protein-rich cake	- Significant for local industries - Enhances soil fertility through nitrogen fixation
Soybean	Legume rich in oil and protein. Prefers well-drained soils.	Derived Savanna Zone	- Biodiesel production - Protein supplements - Livestock feed	- Source of biodiesel and agricultural feedstock

**Table 3.** The Biofuel Production Potential in Edo State, Nigeria

Energy Crop	Biofuel Type	Estimated Production Potential (Tons/Year) *	Agro-Ecological Zone	Key Benefits	Challenges
Oil Palm	Biodiesel	300,000–500,000	Rainforest Zone	<ul style="list-style-type: none"> <li>- High oil yield</li> <li>- Supports biodiesel production and by-products like glycerin</li> </ul>	<ul style="list-style-type: none"> <li>- Land-use conflict</li> <li>- Processing inefficiencies</li> </ul>
Cassava	Bioethanol	200,000–350,000	Rainforest and Derived Savanna Zones	<ul style="list-style-type: none"> <li>- High starch content</li> <li>- Widely grown and adaptable</li> </ul>	<ul style="list-style-type: none"> <li>- Competition with food security</li> <li>- High water requirement</li> </ul>
Sugarcane	Bioethanol	150,000–250,000	Freshwater Swamp Zone	<ul style="list-style-type: none"> <li>- High sugar yield for ethanol</li> <li>- Suited for swampy areas</li> </ul>	<ul style="list-style-type: none"> <li>- High water and labor requirement</li> <li>- Limited cultivation areas</li> </ul>
Maize	Bioethanol	100,000–150,000	Derived Savanna and Rainforest Zones	<ul style="list-style-type: none"> <li>- Multipurpose crop for food and fuel</li> </ul>	<ul style="list-style-type: none"> <li>- Susceptibility to pests</li> <li>- Competition with food security</li> </ul>
Jatropha	Biodiesel	50,000–100,000	Derived Savanna Zone	<ul style="list-style-type: none"> <li>- Non-food crop</li> <li>- Tolerates marginal lands</li> </ul>	<ul style="list-style-type: none"> <li>- Low awareness and adoption</li> <li>- High initial cultivation costs</li> </ul>
Plantain/Banana	Bioethanol	50,000–80,000	Rainforest Zone	<ul style="list-style-type: none"> <li>- High sugar and starch content for ethanol production</li> </ul>	<ul style="list-style-type: none"> <li>- Post-harvest losses</li> <li>- Low processing infrastructure</li> </ul>
Rice	Bioethanol (Husk)	20,000–30,000	Freshwater Swamp Zone	<ul style="list-style-type: none"> <li>- Utilizes agricultural waste (husks)</li> </ul>	<ul style="list-style-type: none"> <li>- Limited processing facilities</li> <li>- Competition with food production</li> </ul>
Groundnut (Peanut)	Biodiesel	30,000–50,000	Derived Savanna Zone	<ul style="list-style-type: none"> <li>- High oil yield</li> <li>- Suited for biodiesel production</li> </ul>	<ul style="list-style-type: none"> <li>- Susceptibility to drought and pests</li> <li>- Limited mechanization</li> </ul>
Soybean	Biodiesel	40,000–60,000	Derived Savanna Zone	<ul style="list-style-type: none"> <li>- High oil and protein content</li> </ul>	<ul style="list-style-type: none"> <li>- Competition with animal feed industry</li> <li>- Limited cultivation areas</li> </ul>

**Table 4.** Estimated Agricultural Crop Residues for Major Crops Grown in Edo State:

Crop	Residue Type	Residue-to-Product Ratio (RPR)	Estimated Residue Production (Tons/Year) *	Uses	Challenges
Oil Palm	Fronds, kernel shells, fibers	3:1	600,000–900,000	- Biomass energy - Mulching - Briquette production	- High transportation cost - Low awareness of residue utilization
Cassava	Stalks, peels	0.3:1	60,000–100,000	- Animal feed - Biogas production - Organic fertilizer	- High perishability - Limited processing infrastructure
Sugarcane	Bagasse, tops, leaves	0.3:1	45,000–75,000	- Cogeneration (electricity) - Biogas production - Mulching	- Seasonal availability - Low residue recovery rate
Maize	Cobs, stalks, husks	1.5:1	150,000–225,000	- Biomass energy - Livestock feed - Composting	- Susceptibility to pests - Inadequate collection systems
Rice	Husks, straw	1.5:1	30,000–50,000	- Biomass energy - Briquette production - Animal bedding	- Dust pollution during processing - Limited recycling facilities
Groundnut (Peanut)	Shells, haulms	1:1	30,000–50,000	- Biomass energy - Animal feed - Organic mulch	- Low mechanization of shelling - Limited large-scale utilization
Plantain/Banana	Leaves, stems, peels	2:1	100,000–150,000	- Biogas production - Mulching - Fiber production	- High moisture content - Post-harvest losses
Soybean	Stalks, husks	1.5:1	60,000–90,000	- Biomass energy - Livestock feed - Soil enrichment	- Residue competition with other agricultural uses
Yam	Peels, vines	0.2:1	20,000–40,000	- Biogas production - Animal feed - Composting	- High moisture content - Limited large-scale recovery

**Table 5.** Waste Residues Generated in Edo State

Resource	Availability	Primary Uses	Potential for Biofuels
Oil Palm Residues	Abundant (20,000–25,000 tons annually)	Bioethanol, biodiesel production	Feedstock for biofuels
Sawdust and Wood Residues	Moderate (15,000–18,000 tons annually)	Heat generation, briquettes	Bioethanol, biogas
Cassava Peels	High (12,000–15,000 tons annually)	Animal feed	Bioethanol, biogas
Rice Husk	Moderate (10,000–12,000 tons annually)	Fertilizer, energy generation	Biogas
Municipal Solid Waste	Significant (200–300 tons/day in Benin City)	Waste-to-energy	Biogas, syngas

**Table 6.** Inventory of Aquatic Weeds for Biofuels Production in Edo State

Aquatic Weed	Scientific Name	Location	Biomass Potential	Biofuel Application	Challenges
Water Hyacinth	<i>Eichhornia crassipes</i>	Benin River Basin, wetlands	High lignocellulosic content	Bioethanol, biogas	High moisture content, harvesting logistics
Duckweed	<i>Lemna spp.</i>	Shallow water bodies, irrigation ponds	Rapid growth, nutrient absorption	Biogas, biodiesel	Small biomass yield, scalability
Cattails	<i>Typha spp.</i>	Wetlands, marshy areas	High cellulose and hemicellulose content	Bioethanol, briquettes	Difficult harvesting, processing requirements
Algae	Various species	Coastal regions, stagnant waters	High lipid content	Biodiesel, bioethanol	Algal bloom management, drying
Reeds	<i>Phragmites spp.</i>	Freshwater wetlands, riversides	High lignin and cellulose content	Bioethanol, biochar	Harvesting complexity
Salvinia	<i>Salvinia molesta</i>	Slow-moving rivers, ponds	Moderate biomass availability	Biogas, composting	Overgrowth in localized areas

**Table 7.** Animal Waste for Biofuels Production in Edo State

Animal Waste Type	Annual Biomass Potential	Biofuel Applications	Estimated Energy Production	Challenges
Cattle Manure	600,000 tons	Biogas, composting	Up to 10,000 cubic meters of biogas annually	Collection and transportation difficulties
Poultry Waste	150,000 tons	Biogas, composting	Biogas production for local energy needs	Storage and handling issues
Pig Manure	100,000 tons	Biogas, composting	Biogas production for cooking and heating	Inconsistent waste generation
Goat and Sheep Manure	50,000 tons	Biogas, composting	Biogas and organic fertilizer	Limited infrastructure for processing
Animal Fats (from pigs and cattle)	Varies by slaughter rate	Biodiesel production	Biodiesel production up to 5,000 liters per year	Processing requirements for biodiesel conversion

## **5. DISCUSSION**

### **5.1 Agro-Ecological Zones of Edo State**

The agro-ecological zones of Edo State significantly influence the region's agricultural productivity, ecological sustainability, and economic potential. The diversity across these zones provides distinct opportunities for crop cultivation, livestock farming, and renewable energy development, particularly in biomass production. The rainforest zone, characterized by high rainfall and fertile soil, supports the cultivation of perennial crops such as oil palms, cocoa, cassava, and plantain. This zone holds considerable potential for agro-industrial development due to its abundant resources. Studies, such as those by Abogunrin-Olafisoye et al. (2024), highlight the critical role of oil palm cultivation in food production and biofuel development, particularly biodiesel. However, challenges such as deforestation and soil erosion necessitate the adoption of sustainable land management practices to preserve this zone's productivity. The findings align with research by Ahmed and Olaitan (2024), which highlights the potential of forest zones in Niger state Nigeria for high-value cash crop production. However, the vulnerability of this zone to deforestation and soil erosion requires sustainable land management practices.

The derived savanna zone serves as a transition between the rainforest and drier savanna regions. Its balance of rainfall and dry periods makes it ideal for cultivating crops like maize, soybean, groundnut, and sorghum. This zone aligns with the state's efforts to enhance food security and bioethanol production. Ben-Iwo et al. (2016) emphasizes the zone's suitability for maize and cassava, which are critical feedstocks for ethanol production. However, the seasonal dryness in this zone may limit year-round productivity, highlighting the need for effective irrigation systems to sustain agricultural output. The results corroborate studies by Franke et al. (2018), which emphasize the adaptability of cereal and legume crops in derived savanna areas. However, this zone faces challenges such as seasonal droughts, necessitating the adoption of climate-resilient farming techniques.

The freshwater swamp zone, characterized by low-lying and waterlogged areas, is particularly suitable for crops like rice, sugarcane, and vegetables, making it a hub for flood-tolerant crop production. The zone's proximity to rivers facilitates irrigation but also poses risks such as flooding and salinization. Integrated water management strategies are essential for optimizing agricultural output in this zone while mitigating environmental risks. Studies by Okonkwo et al. (2021) confirm the potential of freshwater swamps in enhancing Nigeria's rice production capacity. Nonetheless, flooding and soil acidity are major concerns that require integrated water management systems.

The floodplain zone, enriched with nutrient-dense alluvial soils, supports the cultivation of rice, maize, and vegetables. These areas are crucial for intensive farming due to their natural fertility and access to water resources. However, seasonal flooding presents both opportunities and challenges. While flooding replenishes soil nutrients, it requires careful planning to harness agricultural potential and minimize environmental damage. These findings resonate with Ndubueze-Ogaraku et al. (2022), which highlight the importance of floodplain agriculture in increasing food security. However, sustainable flood control measures are critical to prevent crop damage and soil nutrient loss.

Compared to other Nigerian states, Edo's agro-ecological diversity offers a broader range of opportunities for food and energy crop cultivation. While states like Niger and Kwara excel in specific agro-ecological zones, Edo's combination of rainforest, savanna, and swamp zones enables a wider array of agricultural activities and renewable energy projects. The agro-ecological zones of Edo State provide opportunities for crop diversification, food security, and biofuel production. The Rainforest Zone supports perennial energy crops like *Jatropha* and oil palm, while the Derived Savanna and Freshwater Swamp Zones are favorable for cassava and sugarcane, key feedstocks for bioethanol. The

agro-ecological zones of Edo State present immense opportunities for agricultural growth and renewable energy development. However, realizing this potential requires a strategic approach that integrates environmental sustainability, technological advancement, and robust policy frameworks. By addressing the unique challenges and leveraging the strengths of each zone, Edo State can achieve ecological and economic stability while contributing significantly to Nigeria's agricultural and energy sectors.

## **5.2 Biomass Inventory-Dependent Biofuel Generation**

Biofuels, typically classified as liquid or gaseous fuels, are primarily derived from biomass. As a key component of the renewable energy sector, bioenergy focuses on producing energy from biomass in a way that maintains sustainability. Biomass-based biofuels are gaining increasing attention due to their potential to reduce reliance on fossil fuels, combat climate change, and enhance energy security. These biofuels include biohydrogen, biogas, biodiesel, and bioethanol, each representing a different stage in biofuel technology development.

First-generation biofuels (1st G) are primarily produced from food crops such as corn, sugarcane, sugar beet, wheat, rapeseed, soybean oil, sunflower, and palm oil. These crops are well-established as biofuel feedstocks, with mature technologies enabling efficient conversion into biofuels. 1st G biofuels are known for reducing atmospheric CO<sub>2</sub> emissions when they replace fossil fuels (Rodionova, et al., 2017). However, their reliance on food crops raises concerns about food security and land use competition, necessitating the exploration of alternative, more sustainable feed stocks.

Second-generation biofuels (2nd G) are derived from non-food biomass, such as agricultural residues, industrial waste, municipal solid waste, sewage sludge, and used cooking oils. These materials, often composed of lignocellulosic biomass (LCBs), are abundant and cost-effective, offering significant potential for large-scale biofuel production. The use of LCBs reduces fuel production costs and minimizes carbon footprints, as these feedstocks have little impact on food production or land use (Yadav, et al., 2020; Ben Hassen Trabelsi, et al., 2018). Biofuels from this generation include biodiesel, bioethanol, biomethanol, biobutanol, biogas, and biohydrogen, typically sourced from agricultural and forestry waste (Chandra, et al., 2012; Jeihanipour and Bashiri, 2015). Technological advancements in 2nd G biofuels have improved the efficiency of converting lignocellulosic biomass into fermentable sugars and other biofuels.

Third-generation biofuels (3rd G) represent a shift towards using microbial feedstocks like algae, bacteria, fungi, and yeast. Algae, in particular, have garnered attention for their high lipid content and rapid growth rate, making them an ideal source for biofuels. Unlike 1st and 2nd G biofuels, algae-based biofuels do not compete with food production and do not require arable land (Kumari and Singh, 2018). Additionally, microorganisms like bacteria, fungi, and yeast can produce biofuels such as bioethanol, biodiesel, and biobutanol from various waste products (Yadav, et al., 2020; Ben Hassen Trabelsi, et al., 2018). Ongoing research is focused on optimizing these biofuel production processes to create more sustainable and circular bioeconomies.

Fourth-generation biofuels (4th G) represent the forefront of biofuel technology, mainly derived from genetically modified organisms (GMOs) such as engineered microalgae, fungi, yeast, and cyanobacteria. This generation leverages advanced biotechnologies like genetic engineering and synthetic biology to improve biofuel production efficiency. 4th G biofuels often involve photobiological solar and electro-fuels, which use biological processes to directly convert solar energy into fuel. This approach, which relies on low-cost, abundant raw materials, has the potential to revolutionize energy storage and sustainability, making 4th G biofuels a leading candidate for

addressing future global energy needs (Aro, 2016). Although still in its early stages, this field promises to offer innovative solutions to energy production and environmental challenges.

The progression from 1st G to 4th G biofuels reflects the growing sophistication and sustainability of bioenergy technologies. While 1st G biofuels have made significant strides in reducing fossil fuel dependence, concerns about food security and land use competition highlight the need to move toward 2nd, 3rd, and 4th G biofuels. These generations represent a more sustainable and circular bioeconomy, where waste and non-food biomass serve as valuable resources for biofuel production. Continued research and development hold great promise for the future of bioenergy, with emerging technologies set to deliver more efficient and environmentally friendly biofuels to meet global energy demands while mitigating climate change.

### **5.3 Agricultural Waste Resources in Edo State**

Agro-waste represents an abundant and renewable source of biomass, originating from a variety of sources such as food processing, domestic activities, commercial kitchens, restaurants, and markets (Sarkar et al., 2017). Edo State is endowed with a vast array of agricultural resources, offering significant potential for bioenergy production. Biomass feedstocks, critical for bioenergy, can be classified into agricultural residues, forestry resources, urban waste, and other materials. The state's agricultural sector is pivotal in generating these feedstocks, positioning Edo State as a key contributor to Nigeria's bioenergy development efforts.

Agriculture in Edo State is predominantly based on traditional smallholder farming systems. Small-scale farmers utilize simple techniques such as bush-fallow cultivation, a practice common in Nigeria (FAO, 2005; Aregheore, 2005). Despite these rudimentary methods, agriculture remains a cornerstone of the economy, contributing two-thirds of Nigeria's total agricultural output (Aregheore, 2005). Historically, agriculture was the backbone of Nigeria's economy before the discovery of oil and continues to play a vital role in GDP and export revenue generation (Aregheore, 2005).

Edo State's humid tropical climate, with an annual rainfall exceeding 2,000 mm in certain regions, supports the cultivation of a wide range of crops. Staples such as cassava, rice, and yams thrive in the region, alongside cash crops like cocoa, oil palm, and rubber, which are prominent in the southern humid zones of Nigeria (FAO, 2005; Aregheore, 2005). The favorable agro-ecological conditions enable the state to maintain its agricultural productivity, contributing significantly to both local and national economies.

Agricultural waste (AW), as defined by the United Nations (1997), encompasses waste generated from farming operations, including manure, harvest residues, fertilizer runoff, and pesticide contamination. These waste streams intersect across modern agricultural practices, spanning crop waste, animal waste, processing waste, and hazardous waste such as pesticides (Nagendran, 2011).

Edo State's rich agricultural landscape offers substantial opportunities for harnessing agricultural waste for bioenergy production. By converting these waste streams into energy, the state can address waste management challenges, reduce greenhouse gas emissions, and contribute to Nigeria's sustainable development goals. Developing efficient waste-to-energy systems in Edo State could serve as a model for other regions, highlighting the potential of agricultural waste as a cornerstone of Nigeria's renewable energy future.

### **5.4 Biomass Feedstocks and Energy Crops**

Edo State's agricultural resources present significant potential as biomass feedstocks for bioenergy production, with energy crops such as sugarcane, cassava, sweet sorghum, and maize standing out due

to their high energy content and adaptability to the region's environmental conditions. These crops are particularly valuable because they can be cultivated on both prime and marginal or degraded lands, which helps optimize land use and ensures the effective utilization of available agricultural space. Additionally, Edo State's humid tropical climate, combined with consistent rainfall patterns, makes it an ideal environment for the cultivation of these energy crops, further enhancing their suitability for biofuel production (Edenhofer et al., 2011; Huber et al., 2006).

Nigeria, including Edo State, is endowed with vast arable land and abundant water resources, both of which are essential for supporting the large-scale cultivation of energy crops and the production of biofuels (Abila, 2010; GOPA, 2015). The state's natural resources create a favorable foundation for growing energy crops, contributing to the potential for sustainable bioenergy solutions.

Among the various energy crops, cassava and sugarcane are particularly notable as key feedstocks for biofuel projects in Nigeria, including those in Edo State. Cassava, a versatile and widely cultivated crop, is primarily used in the production of bioethanol, offering high starch content that can be efficiently converted into renewable energy. In contrast, sugarcane not only serves as a significant source of bioethanol but also provides bagasse, a fibrous residue that can be utilized for electricity generation. Both crops have shown substantial promise in Nigeria's biofuel sector, with growing areas of land being dedicated to their cultivation as part of the country's renewable energy strategy (Abila, 2010; GOPA, 2015). These crops play an integral role in the development of a sustainable biofuel industry in Edo State, supporting both energy production and economic growth in the region.

Also, aquatic weeds in Edo State present a promising opportunity for the development of biofuels, as these plants, often viewed as environmental nuisances, possess high biomass yields and are rich in cellulose, lignin, and sometimes oils, which make them viable feedstocks for bioenergy production. Aquatic weeds such as *Eichhornia crassipes* (water hyacinth), *Pistia stratiotes* (water lettuce), *Salvinia molesta* (giant salvinia), and *Hydrilla verticillata* (hydrilla) are prevalent in many water bodies in Edo State, which are part of the state's extensive river and wetland systems. These species, though typically viewed as invasive, have shown significant potential for use in biofuels, especially as alternative sources of renewable energy.

Recent studies have emphasized the bioenergy potential of aquatic weeds due to their rapid growth and high biomass accumulation. According to Chen et al. (2022), aquatic weeds are among the most prolific biomass producers, and their fast growth cycles and high moisture content make them ideal candidates for biofuel production. The high cellulose content found in these plants is particularly significant because cellulose can be converted into fermentable sugars for bioethanol production. Research by Ezzariai et al. (2021) demonstrated that water hyacinth, one of the most common aquatic weeds, can be effectively utilized for bioethanol production through enzymatic hydrolysis and fermentation processes.

In addition to bioethanol, aquatic weeds are also promising candidates for biogas production. Aquatic plants, especially *Eichhornia crassipes* and *Salvinia molesta*, have been shown to yield high amounts of methane when subjected to anaerobic digestion. This process, as explored by Moretti et al. (2022), produces biogas that can be used for electricity generation, presenting an efficient way to convert aquatic biomass into renewable energy. According to a study by He et al. (2022), the potential of aquatic weeds like water hyacinth in biogas production is further enhanced by their high nitrogen and phosphorus content, which supports microbial activity during anaerobic digestion, leading to higher methane yields.

Furthermore, the oils present in certain aquatic weeds, including *Pistia stratiotes*, have been identified as valuable sources for biodiesel production. Research by Nawaj Alam et al. (2021) found that the oil content in *Pistia stratiotes* can be extracted and converted into biodiesel through transesterification processes. This finding is particularly important for expanding the scope of biofuels in Edo State, where the presence of such weeds can be harnessed to produce biodiesel as an alternative to traditional fossil fuels.

Edo State's favorable climatic conditions, which include abundant rainfall and fertile soil, support the growth of these aquatic weeds. The region's extensive river systems and wetlands are ideal for the proliferation of aquatic plants, which often thrive in nutrient-rich waters, making them both an environmental concern and an untapped resource for bioenergy. Studies by Kaur et al. (2018) have suggested that proper management of aquatic weed biomass, through harvesting and processing into biofuels, could alleviate some of the negative environmental impacts associated with their growth, such as water eutrophication, reduced biodiversity, and disrupted water transport.

Additionally, the harvesting and processing of aquatic weeds for biofuel production offer economic opportunities. The collection, processing, and conversion of these weeds into biofuels can create local employment opportunities and provide income for rural communities involved in the harvesting and conversion process. According to Kaur et al. (2018), the integration of biofuel production from aquatic weeds into local economies could promote sustainable livelihoods and contribute to rural development while addressing the challenges of invasive aquatic weed management.

A comprehensive inventory of aquatic weeds in Edo State is crucial to assess their distribution, biomass potential, and growth patterns. Such an inventory would provide valuable data on the most suitable species for biofuel production and inform strategies for their sustainable management. According to research by Jekayinfa et al. (2020), detailed mapping of aquatic weed species and biomass availability is critical to determine the economic feasibility and environmental impact of large-scale biofuel production projects.

In conclusion, the inventory and potential utilization of aquatic weeds for biofuel production in Edo State presents a unique and promising opportunity for sustainable energy development. By harnessing these abundant yet underutilized aquatic plants, Edo State could contribute significantly to Nigeria's bioenergy sector while addressing environmental challenges, creating jobs, and promoting rural economic development.

## **6. CONCLUSION**

The biomass resource assessment using the inventory approach for biofuel production potential in Edo State has highlighted the significant role of the region's diverse agricultural and aquatic biomass resources in supporting the development of sustainable bioenergy solutions. Through the systematic inventory of various biomass feedstocks, including agricultural residues, energy crops, and aquatic weeds, this study has provided valuable insights into the availability, distribution, and biofuel production potential of these resources.

The assessment has demonstrated that Edo State possesses an abundant supply of biomass, ranging from crop residues such as cassava, sugarcane, and maize, to aquatic plants like water hyacinth and water lettuce, which are often considered invasive but offer high biomass yields suitable for biofuel production. The climate and environmental conditions of Edo State, characterized by favorable rainfall patterns and fertile soil, further enhance the viability of these resources for large-scale bioenergy projects.

By employing an inventory approach, this study has not only mapped the biomass resources but also identified key areas where biofuel production can be maximized, particularly through the cultivation of energy crops and the harvesting of aquatic weeds. These findings suggest that Edo State has the potential to become a significant player in Nigeria's bioenergy sector, contributing to the nation's energy security, reducing greenhouse gas emissions, and promoting sustainable development.

Moreover, the integration of these biomass resources into biofuel production aligns with global sustainability goals, including the transition to renewable energy, waste reduction, and the mitigation of environmental impacts associated with fossil fuel use. The development of biofuel projects based on these resources will also provide economic opportunities, particularly for rural communities, through job creation in biomass harvesting, processing, and bioenergy production.

The results of this biomass resource assessment emphasize the need for further research, policy support, and infrastructure development to fully realize the biofuel potential of Edo State's biomass resources. By leveraging these abundant resources in a sustainable and efficient manner, Edo State can contribute to Nigeria's efforts to diversify its energy portfolio, improve environmental quality, and foster economic growth. Ultimately, the successful implementation of biofuel production projects will enhance Edo State's role as a leader in renewable energy within Nigeria and the broader West African region.

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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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## ASSESSMENT OF DRUG INFORMATION SERVICES AND INFORMATION SEEKING BEHAVIOR AMONG HEALTHCARE PROFESSIONALS IN KADUNA STATE.

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### ABSTRACT

*Drug information service is a specialized service provided by pharmacists to enhance drug knowledge, rational prescribing and reduce medication errors. While information seeking behavior encompasses the information needs and sources consulted to obtain drug information. The study is aimed at assessing drug information services (DIS) and information seeking behavior among healthcare professionals (HCPs), carried out at Barau Dikko Teaching Hospital and Ahmadu Bello University Teaching Hospital, Kaduna State. It adopted a cross-sectional descriptive research study, and convenience sampling technique was used for this study. The study population was 345 healthcare professionals (Doctors, Pharmacists and Nurses) in both selected tertiary hospitals, from which a sample of 208 was drawn. Paper-based and online questionnaire were used. The questionnaires were divided into two sections, with a section for Pharmacists alone, while the other section was for both Doctors and Nurses. Out of 208 questionnaires administered, 190 were retrieved for analysis. Data was analyzed using frequencies and percentages. The findings of the study for Pharmacists showed that patients (32%) maximally utilized the drug information services. It was agreed that Pharmacists provided a satisfactory (51%) drug information, with most queries being on drug availability and cost (65%), adverse drug effects (62%) and drug indication (54%). The common drug information sources consulted by pharmacists was Emdex/Micromedex (80%). In respect to the results on the seeking behavior of other healthcare professionals (HCPs), most HCPs commonly rely on google (57%) and Pharmacists (41%) for their drug information. Furthermore, this study revealed that drug side effects (76%) and indication (72%) are the common drug information requirement by other HCPs. Finally, most HCPs complain of lack of time (48%) and unreliable information on the internet (48%) as a barrier towards seeking drug information. The Drug information services provided by the pharmacists were satisfactory and useful by providing unbiased and reliable drug information. Information needs are prompted by the desire to provide good and accurate healthcare services, revealing that most HCPs had drug information needs. Pharmacists and the internet appeared to be the most accessible options to seek their drug information.*

## **1.0 INTRODUCTION**

Drug information service is a specialized service provided by pharmacists to enhance drug knowledge, rational prescribing, and reduce medication errors (Abdullah et al., 2017). This service is targeted at providing response to the queries sought by health care professionals in solving drug-related problems associated to pharmacotherapy and patient management. One of the most important features of drug information is to be unbiased in its contents. Therefore, the unbiased nature of drug information is of importance to improve patient outcomes and lower adverse drug reactions (ADRs) (Shah et al., 2016). Drug information service encompasses the activities of specially trained individuals to provide accurate, unbiased information, primarily in response to patient-oriented drug problems received from various health-care professionals (Subash et al., 2013). These activities are carried out by trained individuals such as clinical pharmacist and doctor of pharmacy professionals who are qualified, registered and are saddled with the responsibility of providing information to optimize the drug therapy (Mudigubba et al., 2013).

Proper drug information seeking behavior helps to answer clinical questions to enhance patient care by reducing medication errors. All health-care professionals are faced with drug information needs related to the treatment of their patients. There are different ways in which health-care professionals can acquire drug information, which could either be printed or electronic resources to meet their drug information needs. However, with the introduction of electronic source/internet in 1990s, health-care professionals began using the Internet and medical databases to seek drug information (Iyer et al., 2011). Upgrade in technology in the later decade resulted to the use of hand held devices by health professionals to access medical and drug information. These devices such as, tablets and smart phones, as they felt that the use of these devices has reduced medication errors and has improved their clinical decision-making (Rothschild et al., 2002). Seeking proper drug information at the time of need increases health care professional's clinical knowledge, which is a crucial activity in health care delivery services, as this information keeps them updated on the latest medications available for patient treatment and care. "Seeking drug information is important in addressing drug related problems, which is an essential step that begins with identifying the question, to finding the appropriate answers" through the use of various sources which are available (Iyer et al., 2011). Pharmaceutical related knowledge is continuously growing, which has led to a variety of medications for healthcare professionals to use for patient care purposes. Therefore, understanding the knowledge about drug information-seeking behaviors, the best preferred resources and methods of acquiring drug-related information is necessary among different health care professionals, to facilitate access to drug information. Moreover, due to drug information overload and time limitations in seeking drug information, keeping and organizing information are necessary for healthcare professionals to easily access drug information when required in the future.

## **1.2 Statement of Research Problem**

Despite drug information services (DIS) being an effective tool for a better patient care within and outside the hospital setting, many healthcare providers possess inadequate access to both new and existing drug information knowledge to assist them in providing essential health care services (Subash *et al* 2013). Many health professionals rely on observations, internet, advice from colleagues and building experience empirically through their own treatment success and failures (Langat Milton et al., 2016). Consequently, Mohamed (2011) reported that many deaths could have been avoided if health professionals had access to appropriate and reliable health information updates in health care. Therefore, it is necessary to conduct studies frequently to access and analyze the utilization of drug information services, as well as information seeking behavior among other healthcare professionals in the hospital.

## **1.3 Justification of Study**

Drug use is a complex practice, even a small mistake and incomplete information has negative implication in patients, which can result into noncompliance, therapeutic failure, over dosage, medication errors, drug interactions and adverse drug reactions (ADRs). This consequently lead to ineffective and irrational use of drugs (Peter et al., 2017). Therefore, there is an urgent need for an increased drug information services and proper seeking behavior of drug information by healthcare professionals in Kaduna State to combat any patient therapy problems.

#### **1.4 Aim of the Study**

The aim of this study is to assess drug information services, and information seeking behavior among Healthcare professionals in Kaduna State.

#### **1.5 Objectives of Study**

- i. To evaluate the quality of drug information services provided among healthcare professionals.
- ii. To assess the drug information seeking behavior among health care professionals.
- iii. To determine the barriers of seeking drug information

#### **1.6 Research Question**

- i. What is the level of quality of drug information service provided among healthcare professionals?
- ii. What is the level of behavior among healthcare professionals seeking drug information?
- iii. What are the barriers of seeking drug information?

### **2.0 LITERATURE REVIEW**

Drug Information is essential to preventing medication errors. Such information helps towards providing optimum patient care and improve patient outcome. Drug information obtained from commercial sources are often biased, and thus; non-commercial, independent, unbiased source of drug information is to be considered as reliable drug information source. The Drug Information Centre provides accurate, unbiased and reliable drug information to healthcare professionals and patients, provide counselling as well as monitor, identify and document adverse drug reactions (Malone, et al., 2006).

Drug Information can be seen as a written and / or verbal information or advice regarding drugs and drug therapy in response to a request from other healthcare providers, organizations, patients or the general public community. Drug Information Service (DIS) describes activities undertaken by pharmacists in providing reliable drug information to optimize drug use (Kalra et al., 2011).

Quality assurance in drug information services (DIS) ensures the services to be provided, providing them, determining how well the services were provided, and if the services were acceptable, noting some correctional activity to ensure that future services will be acceptable and optimal. In developing countries such as Nigeria, there are few drug information centers (DICs) and are limited by lack of sufficient personnel, revenue and by limited access to current literature. This shows the need for frequent evaluation of the functioning and quality of services provided by the DIC. Therefore, healthcare professionals are saddled with keeping up to date drug information with an increasing number of new drugs and literature.

#### **2.3 History of Drug Information Center**

In 1962, the first drug information center was developed at the University of Kentucky Medical Center (Anand, et al., 2012). In India, Rosemary sharp, a missionary from UK, began the first drug information center at Christian Medical College, Vellore in the early 1970s (Nahla, et al., 2016). Later

the Karnataka State Pharmacy Council (KSPC) established its Drug Information Centre in August 1997 to disseminate unbiased and reliable drug information to healthcare professionals.

#### **2.4 Drug Information Activities**

To be an effective provider of drug information (DI), the pharmacist must exercise excellent oral and written communication skills and must be able to;

- i. Identify and evaluate the DI needs of patients and health care professionals.
- ii. Obtain appropriate and complete background information.
- iii. Use a systematic approach to address DI needs by effectively searching, retrieving, and critically evaluating the literature (i.e., assessment of study design, statistics, bias, limitations, applicability).
- iv. Appropriately identify, communicate, document, and apply the information to the patient care situation (Mishra P, et al., 2008).

A variety of DI activities may be performed by pharmacists, depending on the particular practice setting and need. Every pharmacist should have the skills to perform the following DI activities:

- i. Providing DI to patients, caregivers, and health care professionals.
- ii. Creating and maintaining currency of a variety of print and online educational resources for patients (e.g., tip sheets, pamphlets) and health care professionals (e.g., in-service documents, newsletters) on topics such as optimal medication use, general health, or select clinical questions.
- iii. Educating health care professionals on safe and effective medication-use policies and processes, including development of resources to communicate this information.
- iv. Leading or participating in continuing education services for health care professionals.
- v. Educating pharmacy students and residents.
- vi. Participating in quality improvement research projects and drug cost analyses.
- vii. Contributing to the biomedical literature and providing peer review for other contributors. (Mishra P, et al., 2008).

#### **2.5 Quality of Drug Information**

Seeking drug information is necessary to every clinician activity in the health care settings. Seeking this information is essential for drug problem-solving and is a necessary step in the process that starts with identifying the question, to finding the appropriate answer. Most drug information needs are related to drug therapy, which is required for patients and their diagnosis. Averagely, physicians and nurses had two informational needs for every three patients seen related to either treatment or diagnosis. Seeking drug information appropriately to answer these questions related to treatment or diagnosis important to enhance patient care by limiting drug related problems. Seeking drug information is necessary to keep health care professionals updated on the new happenings concerning drugs. Furthermore, it helps health care professionals in providing accurate diagnosis, following up on patient treatments as well as improving their clinical knowledge.

Health care professionals obtain drug information from a variety of drug information sources. These sources can be classified as commercial sources, which include drug company representatives, drug advertisement. While the non-commercial sources, include text books, medical letters, journal articles, professional meetings, clinical pharmacists, and colleagues. They could also be classified as written sources, which include books, journals, medical letters, drug company advertisements and oral sources; which include professional meetings, hospital pharmacists, and colleagues.

Generally, Sources of information can be classified as:

### **Primary literature:**

They are the foundation on which all other drug information is derived. These include journal publications on drug-related subjects, such as reports of clinical drug trials, case reports, and pharmacological research. The most reliable evidence comes from reports on randomized controlled trials. Proper evaluation of these trials requires considerable experience, and systematic reviews of combined trials may be necessary.

Advantage: up to date and best source of drug information.

Disadvantages: Costly and Time consuming.

### **Examples of Primary sources:**

1. Medical and therapeutics Journal:  
Annals of internal medicine, British Medical Journal, New England Journal of Medicine.
2. Pharmacy journals:
3. American Journal of Hospital Pharmacy, Annals of pharmacotherapy, Journal of Clinical and Hospital Pharmacy.
4. Drug and Toxicology Information and Pharmacology Journal;
5. British Journal of Clinical Pharmacology, Human and Experimental Toxicology.

### **Secondary literature:**

Secondary sources consist of reviews of primary reports. These provide a personal perspective of the literature and can include comments on how the author might apply the information in practice.

Disadvantages: Need to pay for access for most and don't always include full text

Examples are: Pub-Med, Medline, International Pharmaceutical Abstracts, DRUGDEX, Martindale, POISINDEX.

### **Tertiary literature:**

Tertiary literatures are the starting point to identify information as they provide complete overview on a specific topic. They summarize the primary and secondary published literature. Main examples are printed textbooks.

*Advantages:* Convenient, Easy to use, Familiar to most pharmacists.

*Disadvantages:* Older, less current information.

### **Examples of tertiary sources:**

Drug information handbook, Drug interactions Stockley, Handbook of injectables, Martindale, Pharmacopoeias, Physicians desk ref, BNF, USP, Australian formulary, Emdex.

## **2.6 Overview of Drug Information Needs and Seeking Behavior**

Understanding the drug information needs and information-seeking behavior of various healthcare professional is essential as it determines the planning, implementation and operation of information system and services (Avitgis et al., 2011). Literature reviews have revealed that health practitioners need timely, accurate, and up to date drug information that is obtained from reliable sources (Debra et al., 2007). Hence, the working facility and type of task done by healthcare professionals determines their information needs and pattern information use.

Health care professionals may be prompted to engage in seeking drug information in order to meet their needs Younger, (2010). However, drug information needs do not necessarily translate into information seeking behavior; several factors may determine how an individual respond to drug information need (Case, et al., 2005). Information needs are therefore a requirement that drives health professionals into an information seeking process to meet their information needs. Knowledge about

the information needs, information behavior and seeking patterns of health professionals is important to satisfy the information needs and improve the provided health care services.

Health professionals access different drug information sources to get information, but mostly depend on colleagues and medical textbooks or journals. For instance, studies from high-income countries revealed that physicians mostly seek information on limited number of clinical cases, about which they first consult colleagues and printed materials Davies, (2007). A multi-Centre survey, (China, Egypt, Kenya, India, Thailand) of hospital doctors clearly revealed textbooks remain the most commonly consulted source of information on the management of common medical conditions; journals were less popular and computer searching were uncommon (Hellers, et al., 2000). Another source revealed that health professionals used colleagues as their first source of information Younger, (2010).

Studies from low-income countries also revealed that colleagues remained the main source of medical information for health professionals in Uganda (Tumwikirize et al., 2009). Colleagues were mostly consulted due to their availability, affordability, and accessibility. With the development of technology, the practice has started to change overtime. Some recent studies revealed that Internet or electronic resources are the common sources of information for health professionals. In summary, most research shows that health professionals depend on colleagues for drug information (Tannery et al., 2007).

### **2.6.1 Factors affecting utilization of Drug Information service**

#### *Institutional Factors*

According to Cogdill, (2008), drug information need and seeking patterns of healthcare professionals depend on their roles in the healthcare delivery system. Certain factors affect which sources and types of information are used in a given situation. However, there are various barriers that limits health professionals drug seeking behavior. A study by (Tarapanoff et al., 2008) described these factors as personal, emotional, educational, demographic, social/interpersonal, environmental, economic, and source characteristics. The major barriers that limited health care professionals from seeking information in other high-income countries were related to lack of time, limited access to resources (Flynn, et al., 2011), inadequate search skills, cost, too much information, and liability issues Masters, (2008).

#### *Technological Factors*

A study by Davis, (2007) reviewed that the major barriers to information-seeking behavior included unreliability on internet sources, lack of time, inadequate search skills, lack of basic computer skills, and irrelevant materials Davies, (2007). Internet remains one of the most utilized sources to provide drug information. New communication technologies have been greatly used in every area of the healthcare delivery system in recent years, including electronic patient records, access to laboratory results using the Internet, text messaging reminders on dates, and the use of mobile device applications that allow you to have quick access to health information as well as to take a picture of your prescription and text it to your pharmacy for medication refill (Avtgis et al., 2011).

#### *Socio-Demographic Factors*

There are various barriers encountered by health professionals in an effort to meet their information needs which affect their information seeking behavior. These factors include personal, emotional, educational, demographic, and social or interpersonal. A study done by Gavgani, it found that people who are more educated than others use internet for seeking health information (Gavgani, et al., 2013). Another study done by (Bennett et al., 2009) showed that health professionals who are younger may be more likely to use electronic sources.

### **3.0 RESEARCH METHODOLOGY**

#### **3.1 Study Area**

Kaduna State is one of the 36 states of the Federal Republic of Nigeria located in the northwest geopolitical zone of the country. It takes its name from the capital Kaduna, hence it is usually referred to as Kaduna State to distinguish the two. It is ranked 4th by land area and 3rd by population in Nigeria. The population of the state according to 2006 census stands at 6,113,503. The total land mass of the State is estimated at 46,053 sq km which is about 5% of the total land area of Nigeria.

BDTH, Kaduna is a 240 bed capacity hospital located at Lafia Road, City centre, Kaduna North Local Government Area Kaduna State. ABUTH, is a 490 bed capacity hospital located in a town known as Shika along Zaria-Sokoto road in Zaria, Giwa Local Government Area of Kaduna State. BDTH has across its clinical department averagely 25 medical doctors, 103 nurses, 15 pharmacists, while ABUTH Zaria has 42 medical doctors, 122 nurses, 38 pharmacists.

#### **3.2 Study Design**

The research design used in this study was a cross-sectional descriptive design.

#### **3.3 Study population**

This study was carried out in two tertiary hospitals in Kaduna state (Barau Dikko Teaching Hospital (BDTH), Kaduna and Ahmadu Bello University Teaching Hospital (ABUTH), Zaria. Kaduna State.

##### *3.3.1 Inclusion Criteria*

All Doctors, Nurses and pharmacists available in both tertiary hospitals (BDTH and ABUTH) who were willing to participate were included in the study.

##### *3.3.2 Exclusion Criteria*

House officers and Interns of the above listed health professionals.

#### **3.4 Sample Size Determination**

The minimum sample size was determined by using the Taro Yamane Method (Formulated by Statistician, 1967).

$$n=N/(1+N(e)^2)$$

where n=sample size

N= population under study = 345

Note:

Average number of Pharmacists in BDTH and ABUTH is **53**.

Average number of Doctors and Nurses in BDTH and ABUTH is **292**.

e=margin error=0.05

$$n=345/1+345(0.05)^2 = 345/1+345(0.0025) = 345/1+0.9$$

n = 181.6 Respondents

To cater for non-response, 15% (27.2) of the sample respondents were included in the study. The non-response rate was due to the lack of time of healthcare professionals which had a negative effect on the availability of health professionals in the health facilities and non-response. Therefore, a total of 208 questionnaires were administered but 190 were returned.

*Attrition rate of 15%(27.2). Therefore  $181+27= 208$  (Sample size)*

*Sampling = Sample size / Entire population X Population of sub groups*

*Respondents A (PHARMACISTS) =  $208/345 \times 53 = 31$  Respondents*

*Respondents B (DOCTORS) =  $208/345 \times 67 = 40$  Respondents*

*Respondents C (NURSES) =  $208/345 \times 225 = 135$  Respondents*

### **3.5 Sampling Technique**

Convenience sampling technique was used for this study, the questionnaires were distributed on working days, and link to the online questionnaires were distributed through WhatsApp were respondents can log-in and respond.

### **3.6 Data Collection Instrument**

The study was conducted using the physical questionnaire and online questionnaire (Microsoft. forms. office). The Microsoft. Forms. Office is an E-survey tool, used to collect the data. The E-survey offers the following features: (i) allows the researcher to create a set of questions, (ii) makes the questions available to the study participants by sending them an email or sharing a URL and via WhatsApp and (iii) allows for viewing the responses to questions as and when they are answered showing the results in frequencies and percentages. The questionnaires were distributed during working days at both tertiary hospitals (BDTH and ABUTH)

### **3.7 Data Collection**

This was done by the researcher and 2 research assistants. The research assistants were Intern Pharmacists and a Nurse from ABUTH. They were trained on the study criteria and data collection.

### **3.8 Data Analysis**

All answered questionnaires were rechecked for completeness. Data was analyzed via descriptive statistics, using Statistical Package for Social Sciences (SPSS) version 20-software package and variables were presented by means of tables and charts showing results in frequencies and percentage.

### **3.9 Ethical Consideration**

Ethical Clearance was sought from the health research and ethics committee (HREC) of Barau Dikko Teaching Hospital Kaduna and the Ministry of Health Kaduna State. In addition, an informed consent was obtained from individual respondents.

## **4.0 RESULTS**

### **4.1 Results on Drug Information Services Provided by Pharmacists**

This section presents the findings of the study, based on research objectives. The results are presented as follows: socio-demographic characteristics, evaluation of drug information (DI) services and type of queries received from health professionals.

#### 4.2 Sociodemographic Characteristics of Respondents

Out of the 61 respondents, majority were females 35 (57%) were aged 19-28 years 40 (66%), single 43 (70%), Muslims 29 (48%). In relation to the qualifications, majority of the respondents 50 (82%) were B. Pharm holders. Lastly, in relation to their years of service, majority 42 (70%) had work experience within 1-5 years, followed by 11 (18%) with an experience within 6-10 years, and the smallest proportion of 5 (8%) and 2 (3%) with work experience of 11-15 and above 16 years respectively.

**Table 1.** Sociodemographic characteristics of respondents

Characteristics	Frequency (Percentage) N=35(%)	
Gender	Male	14(40)
	Female	21(60)
Age(Years)	19-28	12(34)
	29-38	16(46)
	39-48	5(14)
	>49	2(6)
Marital Status	Married	15(43)
	Single	18(51)
	Divorced	2(6)
Religion	Christianity	15(43)
	Islam	20(57)
Qualification	B. Pharm	23(66)
	Pharm. D	1(3)
	Msc Pharm	11(31)
Years In Service	1-5	12(35)
	6-10	12(35)
	11-15	8(24)
	>16	2(6)

#### 4.3 Mode of drug information Requests

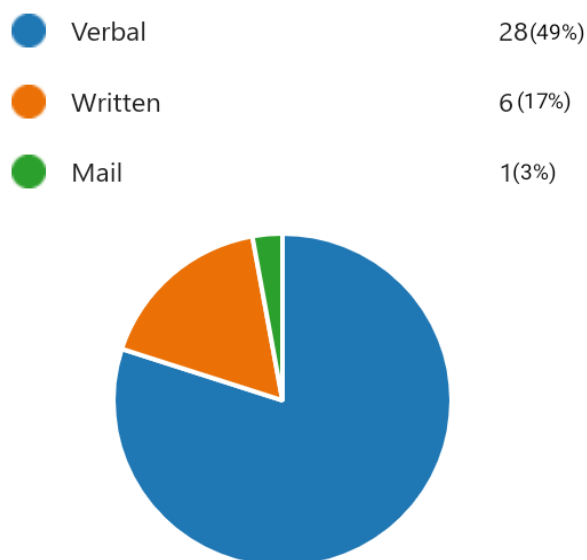
The main mode of request of drug information is by direct access to the pharmacist 28 (44%), followed by phone calls 22(34%)

**Table 2.** Mode of drug information request of the respondents

Response Variables	Frequency(Percentage) N=35
Direct access	28(44)
Ward rounds	11(17)
Query box	3(5)
Phone calls	22(34)

#### 4.4 Common mode of drug information (DI) responses

This analysis revealed most pharmacists 28(80%) provide or respond to drug queries via verbal responses, followed by written form 6(17%) and mail 1(3%).



**Figure 1.** Common mode of DI responses of the respondents

#### 4.5 Average time of responses

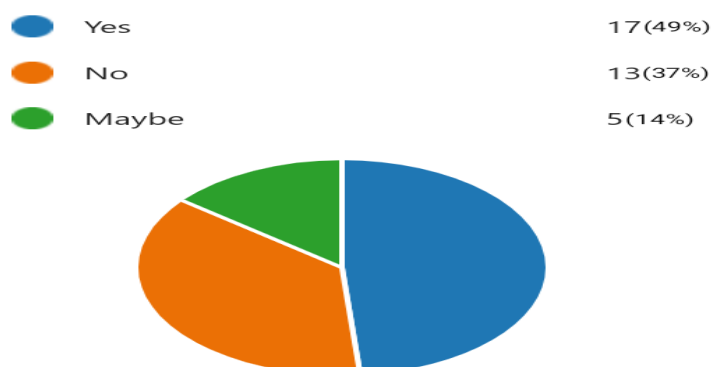
This table summarizes the average time of response, with most pharmacists 20(57%) responding to DI queries within minutes, some provide information immediately 12(34%), within hours 3(9%).

**Table 3.** Average time of responses of the respondents

Response Variables	Frequency (Percentage) N=35(%)
Immediately	12(34)
Minutes	20(57)
Hours	3(9)

#### 4.6 Documentation of received enquiries by pharmacists.

The analysis of documentation of received enquiries showed that most pharmacists 17(49%) document received enquiries, slightly lesser number of pharmacists 13(37%) do not document received enquiries and 5(14%) are not certain of documentation.



**Figure 2.** Documentation of received enquiries by pharmacists

**4.7 Forms of feedbacks received from enquirers**

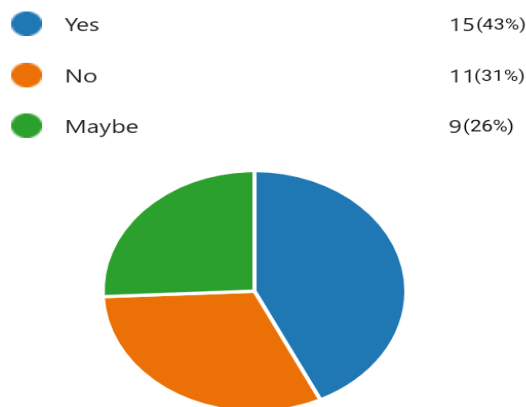
This table shows the feedback or remarks of provided drug information (DI) by the pharmacist, which revealed that enquirers are generally satisfied with obtained DI, with mostly 18(51%) satisfactory remark, with a 0% need for improvement.

**Table 4.** Forms of feedbacks received from enquirers

Response Variable	Frequency (Percentage) N=35(%)
Satisfactory	18(51)
Excellent	10(29)
Good	7(20)

**4.8 Provision of educational programs for health professionals**

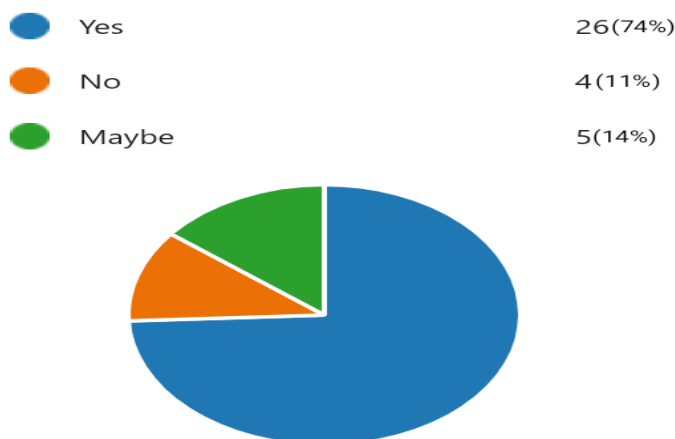
This chart summarizes the pharmacist provision of educational programs for health professionals, revealing that 15(43%) of pharmacists provide this education, while 9(26%) of pharmacists are not sure if they provided this education.



**Figure 3.** Provision of educational programs for health professionals

**4.9 Participation in patient educational programs.**

This chart reveals the analysis of pharmacists ensuring patient educational programs, with most 26(74%) pharmacists participating in the program, while 4(11%) do provide patient education.



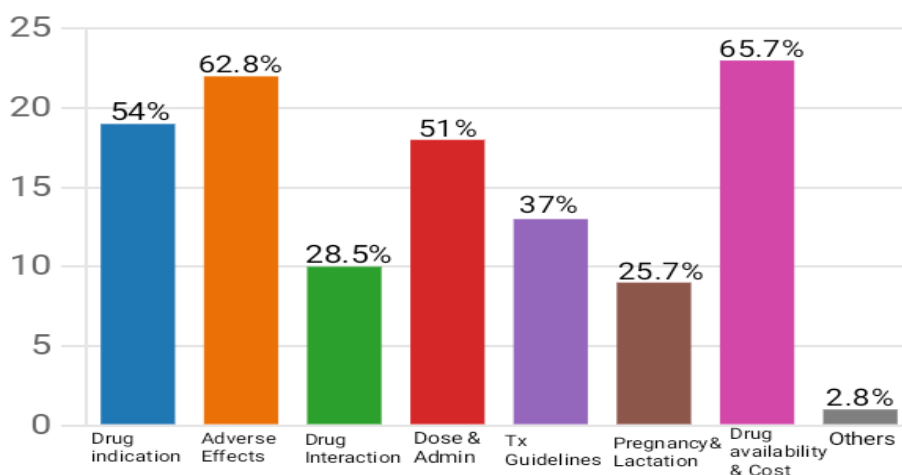
**Figure 4.** Participation in patient educational programs

#### 4.10 Types of Queries Received from Health Professionals

This section explains the results, involving the common queries, status of enquirer, sources of the provided information and frequency of source visit.

##### 4.10.1 Common Drug Information (DI) queries received

This chart reveals the type of queries asked, which shows that the most enquired drug information 23(65.5%) is drug availability and cost, 22(50.8%) adverse effects, 19(36%) drug indication.



**Figure 5.** Common DI queries received: *TX= Treatment*

##### 4.10.2 Status of drug information (DI) enquirer

This chart shows the status of the DI enquirer, with the most 26(32%) being the patients.

**Table 5.** Status of DI enquirer

Response Variables	Frequency (Percentage) N=35(%)
Physicians	18(22)
Pharmacists	15(19)
Nurses	17(21)
Patients	26(32)
Others	5(6)

##### 4.10.3 Common sources of drug information (DI) used by pharmacists

This summarizes the DI sources, most pharmacist 28(83.6%) consult EMDEX/Micromedex, followed by 19 (50.8%) BNF, while BP 1(6.5%) was the least consulted source.

## 5. RESULTS ON DRUG INFORMATION SEEKING BEHAVIOUR AMONG HEALTH CARE PROFESSIONALS (HCPs)

### 5.1 Socio Demographic Characteristics of Respondents

Out of the 155 respondents, majority were males 81(52%), aged 19-28 years 75(49%), mostly single 76(62%) and Christians 101(66%). Most of the respondents 104(64%) were Nurses, and then 44(36%) Doctors, most working in both the in and out patient unit 130(88%), with an access to computer 103(68%) and a working duration within 1-5 years 81(54%).

**Table 6.** Common sources of DI used by Pharmacists

Response Variables	Frequency(Percentage) N=35(%)
EMDEX/Micromedex	28(80)
Martindale	12(34)
BNF	19(54)
BPC	4(11)
Drug leaflets	14(40)
Textbooks	6(17)
Nigerian national drug formulary	11(31)
Meysers side effects on drugs	2(5.7)
Lexicomps drug information handbook	4(11)
BP	1(2.8)

**Table 7.** Socio demographic characteristics of respondents

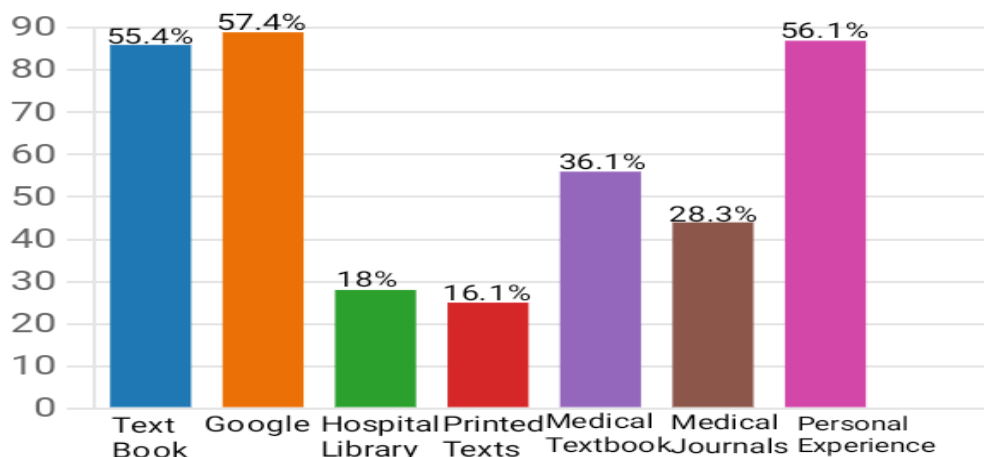
Characteristics	Frequency (Percentage) N=155	
Gender	Male	81(52)
	Female	74(48)
Age(Years)	19-28	75(49)
	29-38	26(16)
	39-48	38(24)
	>49	16(10)
Marital Status	Single	76(62)
	Married	58(38)
	Divorced	6(4)
	Widowed	14(9)
Religion	Christianity	101(66)
	Islam	54(34)
Qualification	Doctors	44(36)
	Nurses	104(64)
Working Unit	In-Patients	11(7)
	Out-Patients	6(4)
	Both	130(88)
Working Experience	Computer Access	103(68)
	No Computer Access	48(32)
Duration Of Practice (Years)	1-5	81(54)
	6-10	19(13)
	11-15	33(22)
	>16	17(11)

## 5.2 Information Seeking Pattern

This section explains the common drug information (DI) sources, frequency of utilizing these sources, the HCPs they consult and frequency, the purpose of DI needs, type of DI needs, form at which this information are shared amongst healthcare professionals (HCPs), documentation of DI, barriers observed when seeking DI and the possible recommendation to overcome the mentioned barriers.

### 5.3 Common drug information sources used by other healthcare professionals (HCPs)

The chart shows the results obtained from the study concerning the common drug information (DI) sources utilized by HCPs in Kaduna State. Most HCPs depend on Google 89(57.4%), personal experience 87(56.1%) the most in providing healthcare services and rarely utilizes 25(16.1%) printed texts.



**Figure 4.** Common DI sources used by other HCPs

### 5.4 Frequency of consulting drug information sources

This result reveals the frequency at which HCPs consult these sources. Most HCPs uses these sources on a daily basis 78(51%), while some only consult these sources when necessary 34(22%), weekly 24(16%) and monthly 8(5%).

**Table 8.** Frequency of consulting drug information sources

Response variable	Frequency (Percentage) N=155(%)
Daily	78(51)
Weekly	24(16)
Monthly	8(5)
When necessary	34(22)
Other	9(6)

### 5.5 Health care professionals (HCPs) consulted for drug information

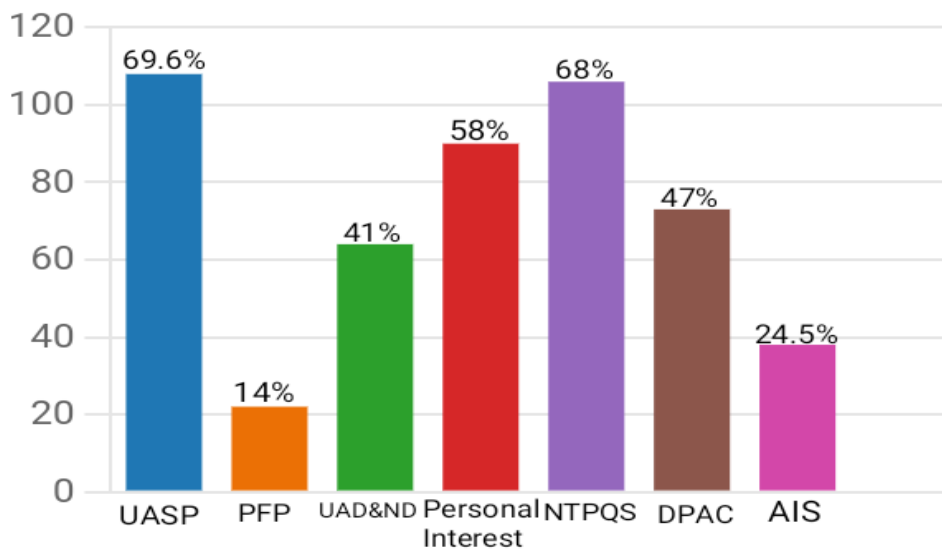
This analysis reveals that most HCPs seek drug information (DI) from pharmacists 62(41%), while others consult all the above listed HCPs 44(29%), Physicians 32(21%) are also consulted for DI, while the least consulted are the nurses 14(9%).

### 5.6 Reasons for drug information (DI) sought

This chart shows the purpose at which healthcare professionals (HCPs) seek DI. Most HCPs 108(69.6%) seek drug information for update on knowledge about a specific patient for optimum care, followed by 106(68%) who seek DI for the need to provide quality healthcare services. The least reason 22(14%) was preparation for publication.

**Table 9.** HCPs consulted for drug information

Response variable	Frequency(Percentage) N=155(%)
Physician	32(21)
Pharmacist	62(41)
Nurses	14(9)
All the above	44(29)
Other	1(1)



**Figure 5.** Reasons for DI sought

UASP= Update about specific patient, PFP= Preparation for publication, UAD&ND= Update about disease and new drug, NTPQS= Need to provide quality service, DPAC= Disease prevention and control, AIS= Adequate information searching.

### 5.7 Common drug information (DI) sought

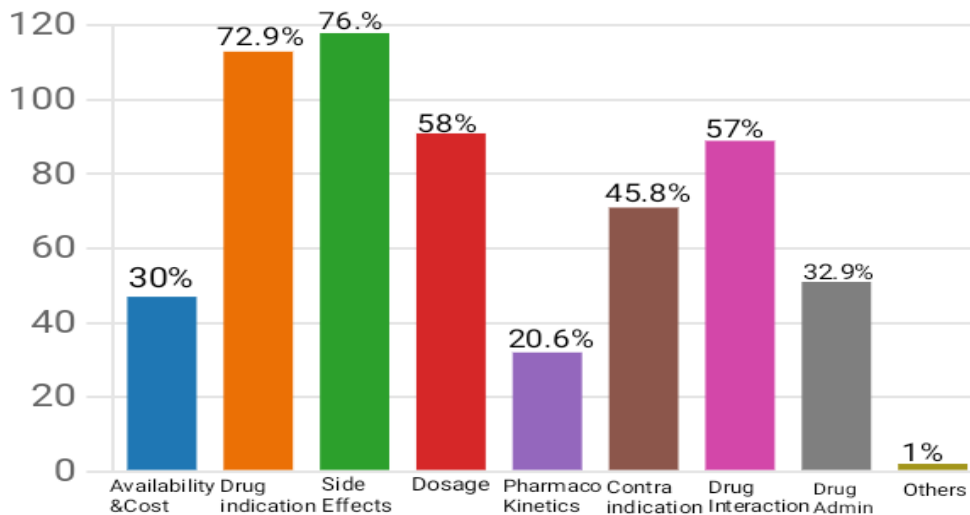
This reveals the analysis on the common DI needs by HCPs in Kaduna State. Most DI sought were about side effects 118(76%) and drug indication 113(72.9%). While the least were about 32(20.6%) pharmacokinetics and 2(1%) other related DI

### 5.8 Channel of communicating drug information (DI)

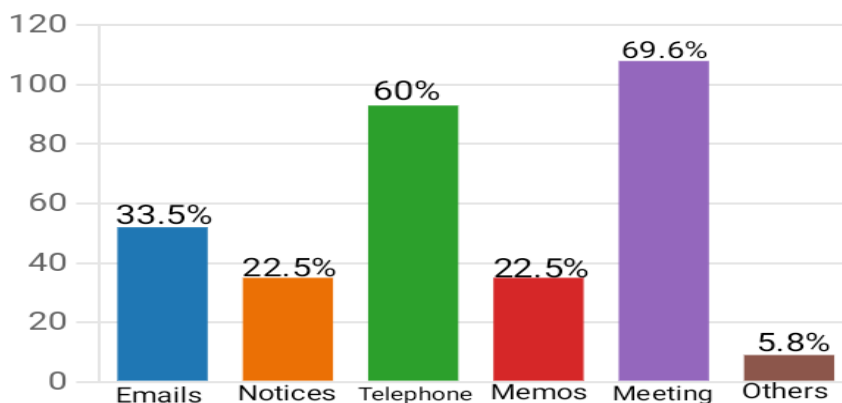
These results interpret the channels utilized in sharing DI in HCPs in Kaduna State which will be expressed in a descending order, from meeting/contact 110(69.6%), telephones 95(60%), emails 54(33.5%), notices 35(22.5%), memos 37(22.5%) and via other means 9(5.8%).

### 5.9 Documentation of received drug information

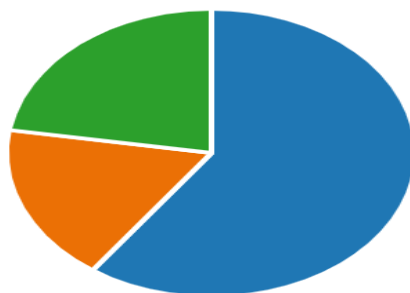
This section reveals if HCPs document received DI for further consumption, with most of HCPs 88(60%) appeared to keep/document received DI for continuity of use, and some appeared to be unsure 33(22%) of documentation, then 26(18%) of HCPs do not keep records of received DI.



**Figure 6.** Common DI sought



**Figure 7.** Channel of communication DI

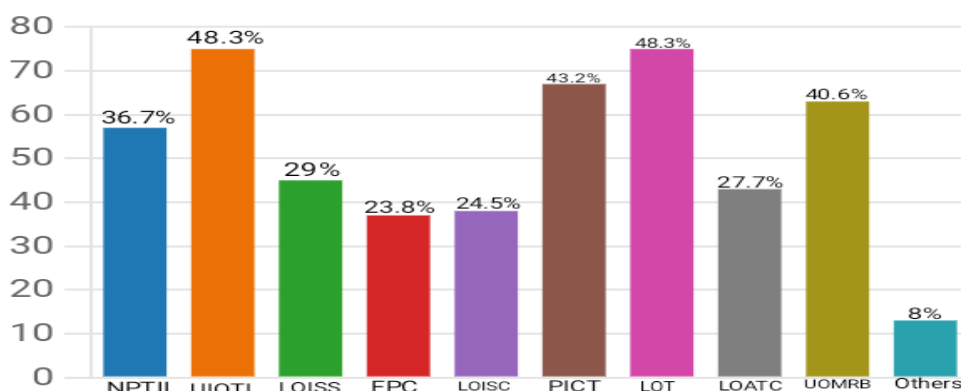


**Figure 8.** Documentation of received DI

### 5.10 Common barriers of seeking drug information (DI)

This obtained results identifies the most possible barrier of seeking DI by HCPs in Kaduna State. The most common barriers are lack of time (48%), Unreliable information on the internet (48%), and poor ICT infrastructure 43.2%. The least barriers were lack of information sharing culture (24.5%) and frequent power cut (23.8%).

NPTII= Negative perception towards internet information, UIOTI= Unreliable information on the internet, LOISS= Lack of information searching skill, FPC= Frequent power cut, LOISC= Lack of information sharing culture, PICT= Poor ICT infrastructure, LOT= Lack of time, LOATC= Lack of access to a computer, UOMRB= Unavailability of medical reference book.



**Figure 9.** Common barriers of seeking DI

### 5.11 Common recommendations to overcome these barriers

**Table 10.** Recommendations to overcome barriers of seeking drug information

Barriers	Recommendations
Lack of information sharing culture	Encourage information sharing culture Good rapport with colleagues
Unavailability of medical reference book Poor ICT Infrastructure	Increase the availability of medical reference books Good ICT Infrastructure and adequate number of qualified pharmacists Constant availability of internet network (WiFi)
Frequent power cut	Provision of adequate power supply Increase access to computer
Others	Equip hospital library
Others	Financial allocation to the hospital to upgrade drug information service
Others	We should not work in isolation...it should be a collaborative effort
Lack of time Unreliable information on the internet	Proper time management Hospitals should have a running drug information center
Lack of access to computer	Provide computers for easy access to drug information, and proper documentation of information

## **6. DISCUSSION**

Drug information services is a complex process that integrates variable sources of drug information and expressing this information. Due to the high rate of increase in the need for essential healthcare and drug information needs, it has become necessary for pharmacists to stay abreast on the latest findings in the drug world (Langat Milton, 2012).

Responses from Pharmacists revealed that patients (32%) maximally utilizes the drug information services in comparison to other enquirers. This finding is in contrast to a study conducted in Saudi Arabia by (Abdullah et al., 2017) whose findings showed that physicians were the major users of drug information services. This is possibly due to Pharmacists high involvement in ward rounds along-side Physicians and other health professionals.

This study also indicated that most pharmacists are consulted via direct access (44%) for drug information queries, which appeared to be one of the fastest and easiest ways of obtaining drug information, and this is possibly due to good Patient-Pharmacist communication. This result matches the findings done in South India by (Kandavalli et al., 2017), which revealed that (38.8%) of queries were received by direct access to the Pharmacist.

Most pharmacists (80%) appeared to provide drug information responses verbally, rather than in a written form (17%), with an average response time within minutes (57%). This observed result appeared to be in contrast to the study conducted in Bengal by (Jayasutha et al., 2011) which revealed that majority of queries were responded to within a day (86%). These differences could be as a result of previous experiences, documentation of past received queries and consistent improvement of drug knowledge. Despite providing drug information majorly within minutes, most pharmacists got a feedback response of providing a satisfactory (51%) drug information, which appears to be in contrast to the study done by (Walli et al., 2015), whose findings showed that majority of enquirers rated the provided drug information as good (90%), rather than satisfactory. This explains the exposure of some pharmacists to research and frequent access to reliable information sources in order to optimize healthcare services.

In determining the common queries received by pharmacists, this study revealed that most drug information sought were about (65.5%) drug availability and cost, followed by (50.8%) drug adverse effects and (36%) drug indication, which is attributed to both patients and physicians being concerned on the safety, tolerability and possible alternatives of drug in question they are either consuming or prescribing. This finding appeared to be closely related to a study done in Germany by (Marcel et al., 2011) which showed that the highest drug information sought were on (16%) adverse drug reaction. Another study by (Subash et al., 2013) showed that the most common queries were about drug indication/therapy (34%).

According to categorization of the common drug information sources, the most consulted source by pharmacists were (83.6%) EMDEX/Micromedex (Computerized information database), BNF (32%) and drug leaflet (39.3%). This might be because of ready availability of the sources and its ease of use as reference source in comparison to all other sources. This result matches the findings of (Vishwanath et al., 2020), whose results revealed that the highest consulted drug information source was EMDEX/Micromedex.

Furthermore, most pharmacists (49%) document received enquiries, which is crucial for pharmacists to easily access drug information when needed in the future. Most Pharmacists, (43%) provide educational programs for health professionals, and also (74%) participate in patient educational programs, possibly because patients were the most enquirers of drug information.

Regarding information seeking behavior among healthcare professionals aside pharmacists, this study indicated that all study participants had information needs, which concurred with (Pakenham-Walsh and Bukachi, 2009) who argued that information is essential in the healthcare system, especially in delivery of assigned roles and responsibilities.

Amongst all healthcare professionals, pharmacists, (41%) were consulted the most for drug information, possibly due to their known excellent drug knowledge. Although, some of these healthcare professionals rely on electronic sources/google (57.4%), personal experience (56.1%) and textbook (54%) as sources for drug information. This shows similarity to a study done in Nigeria by (Mandu et al., 2020) where most respondents agreed to utilize electronic sources/google and textbooks as their source of drug information. A possible reason could be due to technological advancement and the ease of using this source, which relates to the socio demographic characteristics of the respondents within the age group of 19-28 years (48%) who were more exposed to the use of handheld devices than the older ones. Another finding to support this notion was done in Birmingham by (Bennett et al., 2009), which revealed that health professionals who were younger maybe more likely to use electronic sources when seeking drug information.

In regards to the common drug information sought, side effects (76%) and drug indication (72.9%) were the predominant drug information sought. This is possibly due to the importance of this drug knowledge in patient care, where error in drug use and high toxicity are considered life threatening. This result closely matches the finding in the study done by (Peter et al., 2017), where (21%) and (16%) were also on side effects and drug indication respectively.

The common reasons for drug information sought by respondents were mostly (69.6%) update on knowledge about patient and (68%) on the need to provide quality services. This is attributed to the passion and desire of healthcare professionals to provide good healthcare services and perform their duties accurately to prevent errors. This result is comparable with that of (Jeevangi et al., 2012) which showed (46%) and (15%) respectively.

Sharing of available and accurate drug information in a timely manner encourages health professionals to seek and communicate drug information to colleagues to keep each other updated. According to this study, the most utilized channel (69.6%) for sharing/communicating drug information is by meeting/contact, which appeared to be in line with a study done in Kenya by (Langat Milton, 2012) which showed (35.2%) due to urgent need of drug information in question.

Lack of time (48.3%) and Unreliable information on the internet (48.3%), has greatly affected and pose barriers towards seeking drug information according to this study. A probable reason for these barriers may be due to limited number of staff resulting to high patient ratio to the staff and the internet being a platform where anyone can upload information and the validity not certain. This result appeared to be in contrast to a study conducted in Nigeria by (Mandu A et al., 2020), where the predominant challenges faced in seeking drug information were unsteady power supply (89%), inadequate information in the library (80%), and (80%) poor information sharing culture among colleagues.

## **7. CONCLUSION**

Lack of appropriate drug information is one of the main cause of irrational drug use, leading to potential drug problems, therapeutic failure and adverse drug reaction. But, the enhanced utilization of drug information services is an effective and essential tool for better patient care. This study revealed that pharmacists provided a satisfactory and quality drug information services, utilizing

Emdex/Micromedex as their source for drug information, which can be considered a reliable source of drug information.

The combination of drug information needs and the sources consulted makes up information seeking behavior. This study showed that other healthcare professionals (HCPs) possess an average seeking behavior as they rely on google, personal experience and pharmacists for their drug information. The common drug information sought were on drug side effects and indication. Although, certain factors such as unreliable information on the internet and lack of time appeared to be the major barriers of seeking drug information by other HCPs.

Therefore, it can be concluded that quality drug information services are being provided by Pharmacists in Kaduna State. Although, other HCPs possess an average drug information seeking behavior. But, adequate availability of reliable information sources, and easy accessibility would motivate good drug information services and seeking behavior among healthcare professionals in Kaduna State.

## **8. RECOMMENDATIONS**

1. Healthcare professionals, especially Pharmacists should always stay updated on drug information, especially that information concerning drug indication and adverse drug effects.
2. Patients should be well educated about their medications.
3. Rather than relying on internet for drug information, healthcare professionals should consult authorized reference materials or books for their drug information.
4. Healthcare professionals should imbibe drug information sharing culture.
5. Set up a constant running drug information centers in all hospitals.
6. There is a need to frequently carry out research to access drug information services of pharmacists as well as the seeking behavior of other healthcare professionals due to rapid increase and availability of drug options over time.

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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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## ASSESSMENT OF THE ECONOMIC AND SOCIAL IMPACTS OF ARTISANAL SAND QUARRYING: A CASE STUDY OF RAFINGUZA COMMUNITY, KAWO, KADUNA STATE

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### Abstract

*This study presents a cost-benefit analysis of artisanal sand quarrying in Rafinguza, Kawo, Kaduna State, with a focus on its economic, social, and environmental impacts. The findings show that artisanal sand quarrying serves as a significant source of livelihood for many, with 60% of participants fully employed in the industry, primarily earning moderate monthly incomes ranging from ₦51,000 to ₦100,000. Despite its economic benefits, the study reveals notable environmental degradation, with 80% of participants observing adverse effects such as riverbank erosion, water pollution, and loss of vegetation. Furthermore, 60% of workers reported health risks associated with quarrying, particularly respiratory issues due to dust exposure. The study also found a weak regulatory framework, with 60% of respondents unaware of policies governing sand mining and 70% perceiving weak enforcement. These results underscore the dual nature of artisanal sand quarrying—providing economic benefits while causing significant environmental and health challenges. The study recommends adopting sustainable quarrying practices, strengthening government regulations, and raising awareness about the environmental and health risks, alongside research into alternative building materials to reduce the pressure on sand resources.*

### 1. INTRODUCTION

Artisanal sand quarrying is a crucial economic activity in many rural and peri-urban regions, especially in developing countries, where access to natural resources is vital for local livelihoods. In Rafinguza community, located in Kawo, Kaduna State, artisanal sand quarrying has become a significant source of income for many residents. The informal sector, characterized by small-scale sand extraction using basic tools and minimal regulation, has grown due to the increasing demand for sand in the construction industry. Sand is a fundamental material in the production of concrete, road building, and various other infrastructure projects. This growing demand has further solidified the importance of artisanal sand quarrying, which supplies the raw materials required for these activities, contributing significantly to economic development in the region (Padmalal and Maya, 2014).

Artisanal sand quarrying typically involves manual labor, with minimal use of advanced machinery or technological processes. This method of extraction is common in regions like Rafinguza, where sand is

essential for constructing homes, roads, and other infrastructure projects (Mwaipopo et al., 2004). Due to its low barriers to entry, artisanal quarrying provides an opportunity for income generation, especially for individuals in rural and peri-urban communities who may lack access to formal employment opportunities. This form of mining enables many to earn a livelihood, with the activity benefiting not just the miners but also supporting local businesses, including transport services, tool supply stores, and construction-related enterprises. However, despite its evident economic advantages, artisanal sand quarrying raises significant concerns regarding its sustainability and the long-term consequences for both the environment and public health.

Despite these challenges, artisanal sand quarrying remains a valuable source of income for many in Rafinguza. The need for a comprehensive cost-benefit analysis arises from the need to evaluate whether the economic benefits derived from this activity justify its environmental and social costs. A detailed cost-benefit analysis will provide insights into the sustainability of the practice, weighing the economic advantages against the long-term environmental and social costs. By examining both the direct and indirect impacts of artisanal sand quarrying, stakeholders—ranging from local miners to policymakers—can make informed decisions about how to regulate and improve the practice. This analysis will help determine if short-term economic gains are worthwhile or if the community should seek more sustainable, regulated alternatives that balance both economic development and environmental preservation.

This paper, therefore, seeks to conduct a comprehensive cost-benefit analysis of artisanal sand quarrying in Rafinguza community, Kawo, Kaduna State. It will assess the economic benefits generated from sand mining activities and evaluate whether these outweigh the environmental and social costs. The findings of this analysis will provide valuable insights for policymakers, enabling them to develop regulations that can promote sustainable sand mining practices, safeguard the environment, and ensure the well-being of the local population. Through this analysis, the study aims to offer practical recommendations for regulating artisanal sand quarrying and making it more sustainable for future generations.

In light of these concerns, this study is critical for determining the sustainability of artisanal sand quarrying in Rafinguza. It will examine whether the economic benefits from this practice are sustainable in the long term, given the associated risks and challenges. Through this cost-benefit analysis, it is hoped that more informed decisions can be made regarding the regulation and improvement of sand quarrying practices in the region, thus ensuring that this vital economic activity can continue without sacrificing environmental health or community well-being.

## **2. METHOD**

The methodology for this study employed a mixed-methods approach to assess the costs and benefits of artisanal sand quarrying in Rafinguza, Kawo, Kaduna State, focusing on economic, social, and environmental impacts. The study was conducted in Rafinguza, a region known for its high demand for sand in construction activities, making it a suitable location for this analysis. A purposive sampling method was used to select 100 respondents, including 50 quarry workers, 30 local residents, and 20 government officials and contractors. Primary data was collected through structured surveys and semi-structured interviews, aimed at gathering information on income, employment, living conditions, environmental perceptions, and the regulatory framework surrounding sand quarrying. Field observations were also conducted at quarry sites to assess working conditions and environmental impacts. Secondary data was gathered from government reports, academic articles, and local studies on sand quarrying in the region, providing context for the economic and environmental effects. Data analysis involved a cost-benefit analysis (CBA) to quantify the economic impacts, including income generation and infrastructure development, alongside the costs of environmental degradation, health risks, and social conflicts. Environmental impact analysis examined land degradation, deforestation, and water pollution, while social impact analysis evaluated local employment conditions, health, and community conflicts. Ethical considerations were prioritized, with informed consent obtained from all participants, ensuring confidentiality and voluntary participation throughout the study. This methodology allowed for a comprehensive understanding of the multifaceted impacts of artisanal sand quarrying in Rafinguza.

### 3. RESULT

**Table 1.** Results of respondents based on Demographic Information

Question	Response Option	Frequency (n)	Percentage (%)	Interpretation
Age	Under 18	3	6%	Few participants are minors.
	18–30	15	30%	A significant portion are young adults.
	31–40	20	40%	Most participants are middle-aged adults.
	41–50	8	16%	Some participants are in their 40s.
	51+	4	8%	Few are senior citizens.
Gender	Male	35	70%	Majority of participants are male.
	Female	15	30%	Considerable female representation.
Education Level	No formal education	5	10%	Few participants lack formal education.
	Primary school	15	30%	A significant portion completed primary.
	Secondary school	20	40%	Most participants have secondary-level education.
	Tertiary education	10	20%	A smaller group attained tertiary level.
Years in Quarrying	Less than 1 year	8	16%	Few participants are new to quarrying.
	1–3 years	12	24%	A fair portion have mid-level experience.
	4–5 years	20	40%	Most participants are experienced.
	Over 5 years	10	20%	A significant group are industry veterans.
Employment Type	Full-time	30	60%	Majority are fully employed in quarrying.
	Part-time	12	24%	Some participants work part-time.
	Occasional	8	16%	Few work occasionally in the industry.

**Table 2.** Results of respondents based on Economic Aspects of Artisanal Sand Quarrying

Question	Response Option	Frequency (n)	Percentage (%)	Interpretation
Daily Sand Extraction	Less than 1 ton	10	20%	Few participants extract minimal quantities of sand daily.
	1–3 tons	20	40%	Majority extract moderate quantities daily.
	4–6 tons	15	30%	A significant group extracts larger quantities.
	More than 6 tons	5	10%	Very few extract the largest amounts daily.
Cost per Ton of Sand	Less than ₦50,000	8	16%	Few participants incur lower costs per ton.
	₦51,000 - ₦100,000	32	64%	Majority incur mid-range costs per ton.
	More than ₦100,000	10	20%	Some participants face high costs per ton.
Monthly Income	Less than ₦50,000	12	24%	A fair portion earns minimal income.
	₦51,000 - ₦100,000	25	50%	Most participants earn moderate income.
	More than ₦100,000	13	26%	A considerable group earns substantial income.
Primary Income Source	Direct sales of sand	30	60%	Most participants earn directly from sand sales.
	Payment for loading/transportation	20	40%	Significant earnings also come from transport and loading activities.
Major Costs Involved	Labor costs	25	50%	Labor constitutes the majority of operational costs.
	Transportation costs	15	30%	Transport forms a significant cost component.

Question	Response Option	Frequency (n)	Percentage (%)	Interpretation
	Equipment and tools	8	16%	Tools and equipment represent a smaller cost.
	Environmental management	2	4%	Environmental expenses are minimal.

**Table 3.** Results of respondents based on Environmental Impacts

Question	Response Option	Frequency (n)	Percentage (%)	Interpretation
Environmental Degradation	Yes	40	80%	Majority observe environmental degradation caused by quarrying.
	No	5	10%	Few participants report no degradation.
	Unsure	5	10%	Some are unsure about environmental impacts.
Observed Impacts	Erosion of riverbanks	35	70%	Erosion is the most commonly observed impact.
	Water pollution	20	40%	A significant portion reports water pollution.
	Loss of vegetation	25	50%	Half of participants notice vegetation loss.
	Wildlife displacement	15	30%	Wildlife displacement is moderately observed.
Regulations in Place	Air pollution (dust)	30	60%	Air pollution is a frequent issue reported.
	Yes	10	20%	Few participants are aware of existing regulations.
	No	30	60%	Majority report no regulations.
	Unsure	10	20%	A considerable number are unsure about regulations.

**Table 4: Results of respondents based on Social Impacts**

Question	Response Option	Frequency (n)	Percentage (%)	Interpretation
<b>Community Impacts</b>	Creates jobs	40	80%	Majority view quarrying as a job creator.
	Contributes to local economy	30	60%	A significant portion believes it boosts the local economy.
	Leads to social conflicts	10	20%	Few participants report conflicts due to quarrying.
	Negatively affects health	15	30%	Health concerns are moderately reported.
<b>Health Risks</b>	Yes	30	60%	Majority identify health risks associated with quarrying.
	No	10	20%	Few do not see any health risks.
	Unsure	10	20%	Some participants are unsure about health risks.

**Table 5: Results of respondents based on Regulatory and Policy Framework**

Question	Response Option	Frequency (n)	Percentage (%)	Interpretation
<b>Awareness of Policies</b>	Yes	15	30%	A minority are aware of relevant policies.
	No	30	60%	Majority are unaware of policies.
	Unsure	5	10%	Few are unsure about policy awareness.
<b>Government Regulation</b>	Strong enforcement	5	10%	Few perceive strong regulatory enforcement.
	Weak enforcement	35	70%	Most believe regulations are weak.
	No regulation	10	20%	Some report no regulatory presence.

#### **4. DISCUSSION**

The findings of this study reveal significant insights into the demographic, economic, environmental, social, and regulatory aspects of artisanal sand quarrying. A comparative analysis with existing studies highlights both similarities and unique aspects of the results. The study identified Demographic Information which shows that the majority with (60%) of participants involved in sand quarrying are male, while females account for 40%. This is consistent with research by Mngeni and Motlogelwa (2021), who reported that men dominate artisanal mining activities due to the labor-intensive nature of the work. However, the significant representation of women in this study suggests a shift towards inclusivity, aligning with findings by Kamau and Njau (2019), who noted increased female participation in mining-related activities in developing regions.

The Economic Aspects of the study revealed that most participants (64%) incur mid-range costs of ₦51,000–₦100,000 per ton of sand, and 50% earn a moderate income of ₦51,000–₦100,000 monthly. These results align with Onyeka et al. (2020), who found that artisanal miners often operate on thin profit margins due to high operational costs. However, direct sales of sand as the primary income source for 60% of participants indicates the importance of bypassing middlemen to maximize earnings, a strategy also highlighted by Bolarinwa and Idowu (2018).

Environmental degradation, including erosion (70%) and air pollution (60%), were frequently reported. This finding corroborates the work of Asante et al. (2019), who documented similar environmental impacts in Ghana's artisanal quarrying regions. The low adoption of environmental management strategies in this study (only 4% reported engaging in environmental management) contrasts sharply with studies such as Nwankwo and Eze (2022), who emphasized the critical role of community-based environmental rehabilitation programs in reducing degradation.

The Social Impacts of the study revealed that sand quarrying creates jobs (80%) and contributes to the local economy (60%). These findings echo the observations of Mwangi et al. (2021), who noted that artisanal mining serves as a critical source of livelihood for rural communities. However, the 30% reporting health risks due to quarrying activities, such as respiratory issues and injuries, aligns with studies by Aigbedion and Iyayi (2007), which highlighted the occupational hazards associated with artisanal mining.

The Regulatory Policy Framework shows notable finding is the weak awareness (60%) and enforcement (70%) of regulatory policies governing sand quarrying. This aligns with the findings of Mensah et al. (2019), who identified similar challenges in the enforcement of environmental and mining regulations in sub-Saharan Africa. The lack of strong government regulation exacerbates the environmental and social challenges associated with quarrying activities.

Overall, the findings underscore the dual-edged nature of artisanal sand quarrying as both an economic lifeline and an environmental and social challenge. Comparison with other studies confirms the need for improved regulation, environmental management strategies, and worker safety measures. By addressing these challenges, artisanal quarrying can be transformed into a sustainable industry that benefits both the economy and the environment.

## **5. CONCLUSION AND RECOMMENDATION**

The study reveals that while artisanal sand quarrying provides essential economic benefits by creating jobs and supporting local income, it also leads to significant environmental degradation and health risks. The lack of regulation and sustainable practices raises concerns about its long-term viability. To address these challenges, the study recommends implementing sustainable quarrying practices, strengthening government regulation, raising awareness on health and environmental risks, providing safety training for workers, and investing in research for alternative building materials to reduce reliance on sand extraction.

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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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## PHASE CHANGE MATERIALS FOR RENEWABLE ENERGY STORAGE UTILISATION

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### Abstract

*Solar energy is employed in various thermal storage applications globally. To effectively store renewable energy, the exceptional thermal properties of advanced materials, such as phase change materials, are crucial for optimising solar energy utilisation and enhancing the energy and exergy efficiency of solar absorption systems. This chapter addresses the fundamentals of phase change materials, including selection criteria, operational mechanisms, differentiation of thermal energy storage systems, commercially available PCMs, and the development of PCM thermal properties and durability. This chapter addresses phase change materials (PCM) in solar water heating systems for buildings in India, where 20–30% of electricity is consumed for hot water in urban households, residential, and institutional structures. Examined flat plate collectors (FPC) extensively, which are appropriate for generating warm water at household temperatures of 55 to 70 °C, as they are more cost-effective than evacuated tube collectors (ETC), concentrated collectors (CC), and the integration of various phase change materials (PCM) in solar water heating systems.*

### 1. INTRODUCTION

Renewable energy is an inexhaustible resource that can influence the balance between energy supply and energy demand. Solar energy is a prominent renewable resource alongside wind, hydropower, wave energy, tidal energy, and geothermal energy (Sharma et al, 2007). Most countries receive  $5 \times 10^{15}$  kWh annually, corresponding to an average incident solar energy of between 4 and 7 kWh per m<sup>2</sup>. This can be achieved in various solar energy domains, including solar water heating systems, desalination, solar-thermal collectors, building heating and daylighting, and photovoltaic (PV) cells, among others. Technologists and researchers are

endeavouring to harness greater renewable energy for various devices and systems to mitigate the global energy crisis (Dharma et al, 2016). Thermal energy storage (TES) systems can facilitate the utilisation of renewable energy to mitigate greenhouse gas (GHG) emissions and conserve fossil fuels. It plays a crucial role in the conversion of free energy to mitigate energy consumption (Murray et al, 2014). Thermal energy storage (TES) can be categorised into sensible heat, latent heat, and thermochemical energy (Cot-Gores et al, 2012).

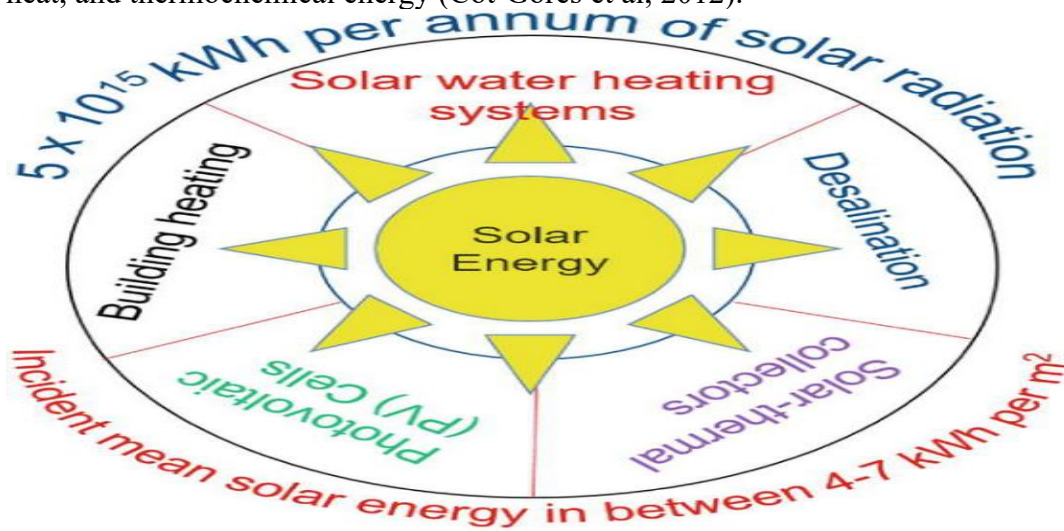


Figure 1. Application of solar energy in different fields.

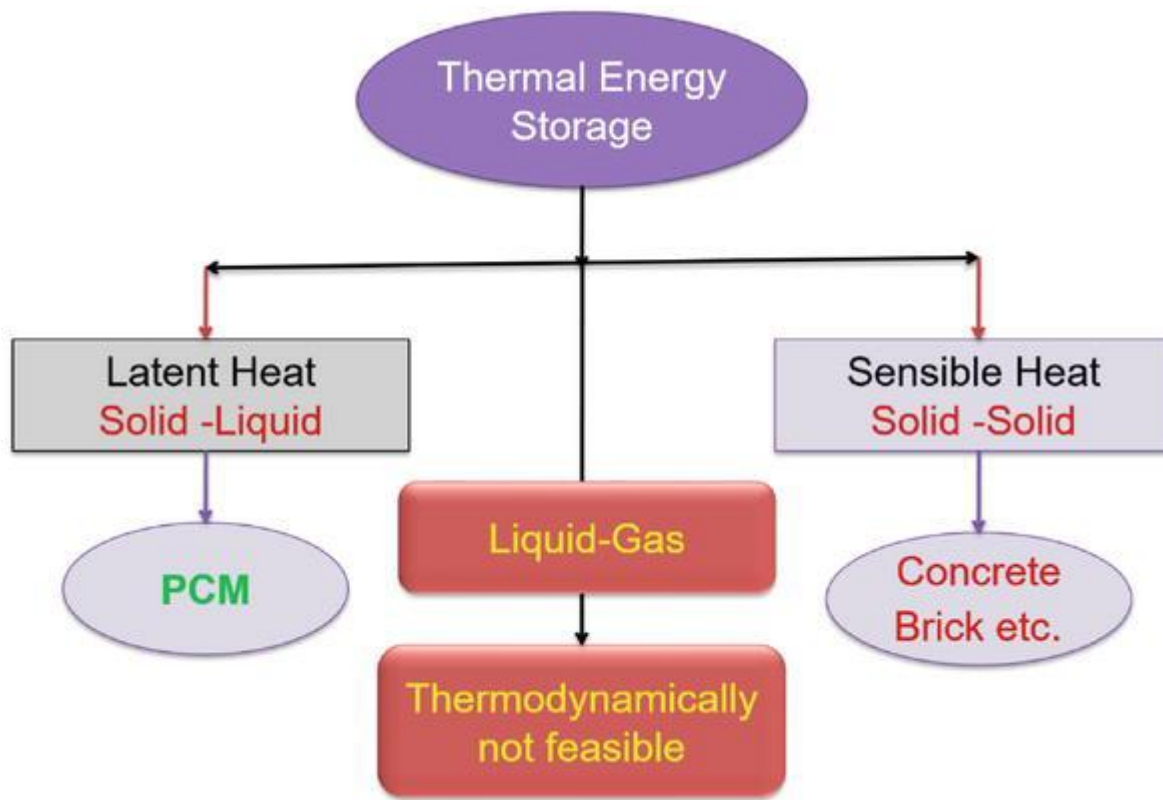


Figure 2. Types of thermal energy storage.

Sensible heat denotes the quantity of energy absorbed without a phase transition, i.e. Solid–solid, liquid–liquid, and gas–gas phase transitions, along with latent heat, denote the quantity of energy absorbed during phase changes, specifically from solid to liquid, liquid to gas, and solid to gas. Thermal chemical energy is the energy stored during a chemical reaction that occurs not only within a specified temperature range but also involves a reversible reaction, with solid to liquid transitions being thermodynamically viable for solar energy applications (Cabeza et al, 2021). Phase change materials (PCMs) are solid to liquid substances that possess the capability to store energy at a constant temperature due to their energy density per unit volume (Figure 2) (Silakhori et al, 2021).

Avargani et al. (2021) implemented two sequential solar collectors containing encapsulated paraffin phase change material. The solitary collector can generate hot water at a temperature of 60°C for 7 hours from dusk until midnight. Fazilati and Alemrajabi (2013) examined the impact of phase change materials in solar water heaters. The energy storage density was enhanced by 39%, and the supply of hot water improved by 25% compared to the absence of PCM. Biwole et al (2013) installed phase change material (PCM) at the rear of the solar collector. The solar collector was modelled using CFD and compared with experimental data. The incorporation of PCM at the rear of the solar collector can sustain the hot water temperature below 40°C for 80 minutes under a continuous solar radiation of 1000 W/m<sup>2</sup>. Hasan et al. (1995, 1994, 2021) have integrated various types of fatty acids into home water heating systems. Fatty acids, including myristic acid, palmitic acid, and stearic acid, exhibiting phase transitions between 50–70°C, are the most promising phase change materials for solar water heating. Manirathnam et al. (2021) synthesised a nanocomposite comprising paraffin wax as a phase change material, incorporating one percent of Sci and CuO. Nano-composite, phase change material (PCM), and non-PCM configurations were examined in an evacuated tube solar water heater for thermal energy storage. The energy efficiencies for the distinct cases were determined to be 33.8%, 38.3%, and 41.7%, respectively, corresponding to the absence of PCM, the presence of PCM, and the use of a nano-composite. Xie et al. (2020) developed a cost-effective and environmentally friendly form-stable stearic acid using coconut shell. The thermal characteristics of the SA/CSC15 composite were 76.69 J g<sup>-1</sup> and 52.52°C, respectively. The SA/CSC composite exhibits potential for energy storage in solar water heaters.

This paper addresses the fundamentals of phase change materials and succinctly examines the criteria for their selection. This text discusses the efficacy of phase change materials (PCMs) in domestic solar water heaters and elucidates how the low thermal conductivity of PCMs can be improved through the incorporation of supporting materials to enhance the efficiency of solar thermal energy storage systems.

## **2. OPERATIONAL MECHANISM OF PHASE CHANGE MATERIALS**

When the ambient temperature exceeds the PCM melting point, the PCM undergoes a phase transition from solid to liquid, absorbing heat from the water storage tank during the night. Conversely, when the ambient temperature falls below the PCM melting point, the PCM releases heat to the environment or water storage tank as it transitions from liquid to solid. Phase Change Materials (PCMs) are effectively utilised as energy storage systems in applications such as heat pumps, solar engineering, and spacecraft.

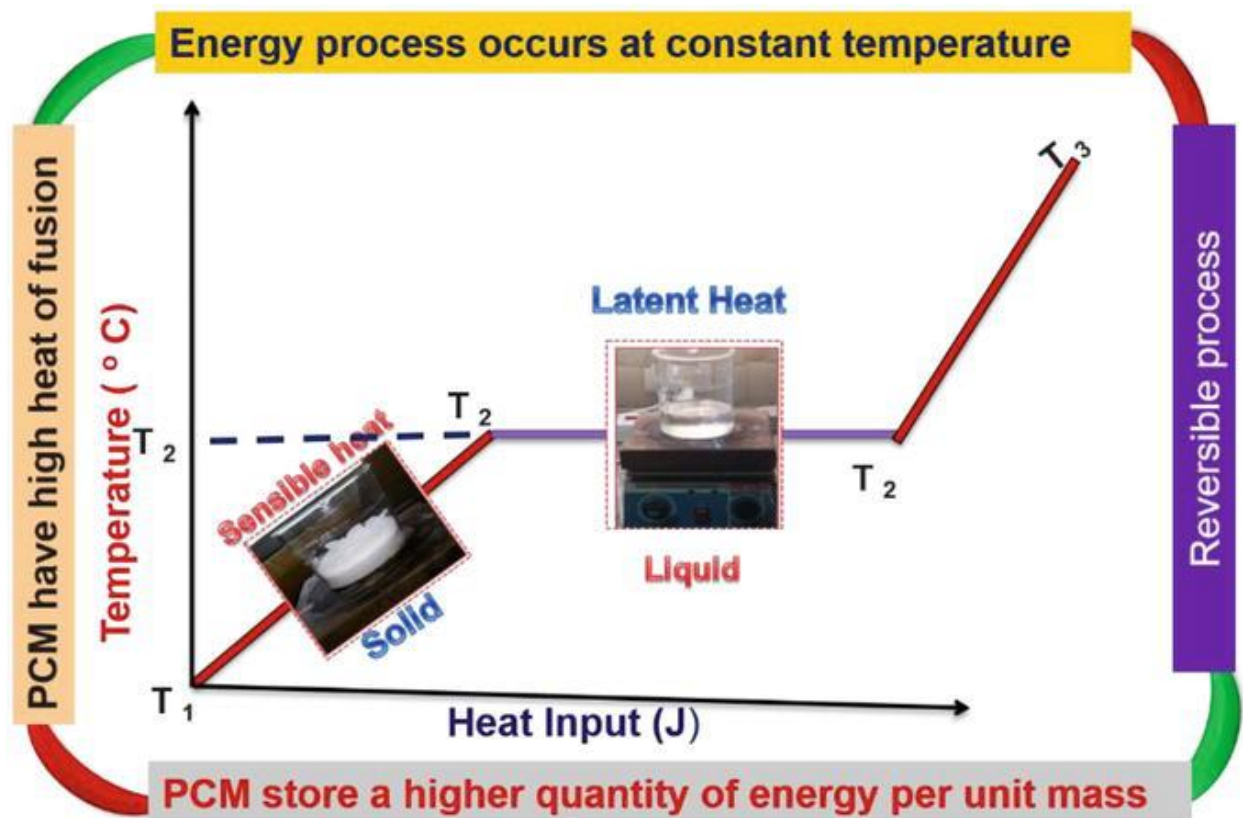
As energy is supplied from the source, the temperature of the PCM increases from the initial temperature ( $T_1$ ) (K) to the final temperature ( $T_2$ ) (K), during which energy is absorbed as sensible heat, transitioning from solid to solid (Mehling et al, 2008). The sensible heat can be computed according to the following Equation. (1)

$$Q_{\text{sensible heat}} = m \cdot C_{ps} \cdot (T_2 - T_1) \quad (1)$$

where  $Q$  represents the quantity of heat retained in the material (kJ),  $m$  denotes the mass of the storage material (kg), and  $\Delta h$  signifies the enthalpy of phase change (kJ/kg). Moreover, heat will continue to be absorbed due to the interaction between liquids. The quantity of phase change materials must be tailored according to the application (Figure 3) (Zalba et al, 2003).

$$Q_{\text{latent heat}} = m \cdot \Delta h \quad (2)$$

where  $Q$  is the amount of heat stored in the material (kJ),  $m$  is the mas of storage material (kg), and  $\Delta h$  is the phase change enthalpy (kJ/kg). Further, heat continues heat will be absorbed due to liquid to liquid. It means that, the amount of phase change materials need to be designed as per the application (Figure 3) (Zalba et al, 2003).



**Figure 3.** Working of phase change material.

$$\text{Total amount energy stored by PCM (Q)} = Q_{\text{sensible heat}} + Q_{\text{latent heat}} + m C_{pl} (T_1 - T_2)$$

$C_{pl}$  is the specific heat of the storage material of liquid state (J/kg·K).

### **3. SELECTION OF PHASE CHANGE MATERIALS**

The selection of phase change materials for solar energy applications must take into account the following qualities.

#### **3.1 Thermal Perspective**

Phase Change Materials (PCMs) must exhibit elevated thermal conductivity during the transitions from solid to liquid and from liquid to solid for effective thermal cycling. Phase Change Materials (PCMs) must possess a high latent heat of fusion to store the appropriate energy while minimising the vessel's volume requirements.

#### **3.2 Physical Perspective**

Phase Change Materials (PCMs) must possess a high specific heat capacity to effectively absorb greater amounts of heat during the transition from solid to solid, known as sensible heat. Phase Change Materials (PCMs) must possess elevated energy density per unit volume.

#### **3.3 Kinetic Perspective**

Phase change materials must exhibit a high nucleation rate to prevent supercooling during the transition from liquid to solid. Elevated crystal growth rates complicate heat recovery.

#### **3.4 Chemical Perspective**

Phase Change Materials (PCMs) must exhibit reversible freeze/melt cycles. PCMs must exhibit chemical stability, meaning the functional groups within the PCMs remain unchanged after multiple temperature cycles. Phase Change Materials (PCMs) must be non-toxic, non-flammable, and non-explosive to ensure safety, as well as non-corrosive to construction materials.

#### **3.5 Economic Perspective**

Phase Change Materials (PCMs) should be readily accessible and inexpensive to reduce the overall cost of solar energy systems.

### **3. CLASSIFICATION OF PHASE CHANGE MATERIALS [24]**

Phase transition materials are classified into three categories: (i) Organic, (ii) Inorganic, and (iii) Eutectic combination.

#### **4.1 Organic Phase Change Materials**

The organic phase change materials exhibit chemical stability, lack supercooling, are non-corrosive, and are non-toxic. Organic phase change materials (PCMs) are categorised into two groups: (i) paraffins and (ii) non-paraffins. Paraffins exhibit chemical inertness, possess low heat conductivity, and undergo significant volumetric variation. Non-paraffins, such as fatty acids, exhibit a higher heat of fusion than paraffins and demonstrate minimal volume change.

#### **4.2 Inorganic Phase Change Materials**

Inorganic phase change materials exhibit a high latent heat of fusion, excellent thermal conductivity, cost-effectiveness, and non-flammability. The majority of them are corrosive to metals. Most inorganic phase change materials are hydrated salts. Hydrated salts possess elevated

energy density and superior thermal conductivity. The disadvantage is that it experiences supercooling.

### 4.3 Eutectic Mixture

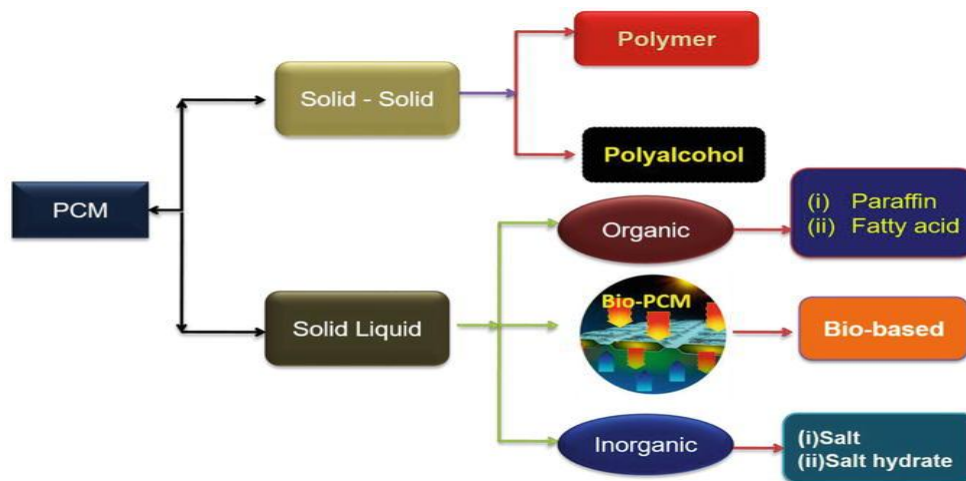
An eutectic mixture comprises multiple phase change materials (PCMs). Eutectic mixes possess a distinct melting point, and their energy density is marginally superior to that of organic phase change materials (PCMs). Eutectics are categorised into three groups: (i) Organic – Organic, (ii) Inorganic – Inorganic, and (iii) Organic – Inorganic (Batens et al, 2010). The optimal temperature range for a eutectic mixture in solar energy applications can be formulated based on Schroder’s Equation. (3) (Shilei et al, 2005).

$$\ln X_A = \frac{\Delta H_A}{R} \left( \frac{1}{T} - \frac{1}{T_f} \right) \quad (4)$$

$X_A$  and  $\Delta H_A$  represent the molar percentage and latent heat of fusion (kJ/kg) of chemical A, respectively.  $T$  and  $T_f$  represent the melting temperatures in degrees Celsius of the mixture and compound A, respectively.  $R$  is the gas constant, 0.8314 kJ/K. molecular.

### 4.4 Biological Phase Change Material

Bio-PCM consists of bio-based materials derived from organic sources. It exhibits lower flammability compared to commercially available phase change materials. The bio-PCM can be formulated within a temperature range of -22.7°C to 78.33°C, contingent upon diverse weather circumstances. These materials are encapsulated in sheets resembling bubbles. Bio-PCM exhibits enhanced thermal characteristics, including specific heat and latent heat of fusion (Murrganantham et al, 2010). Classified phase change materials are being utilised in several domains, including passive and active systems (Figure 4).



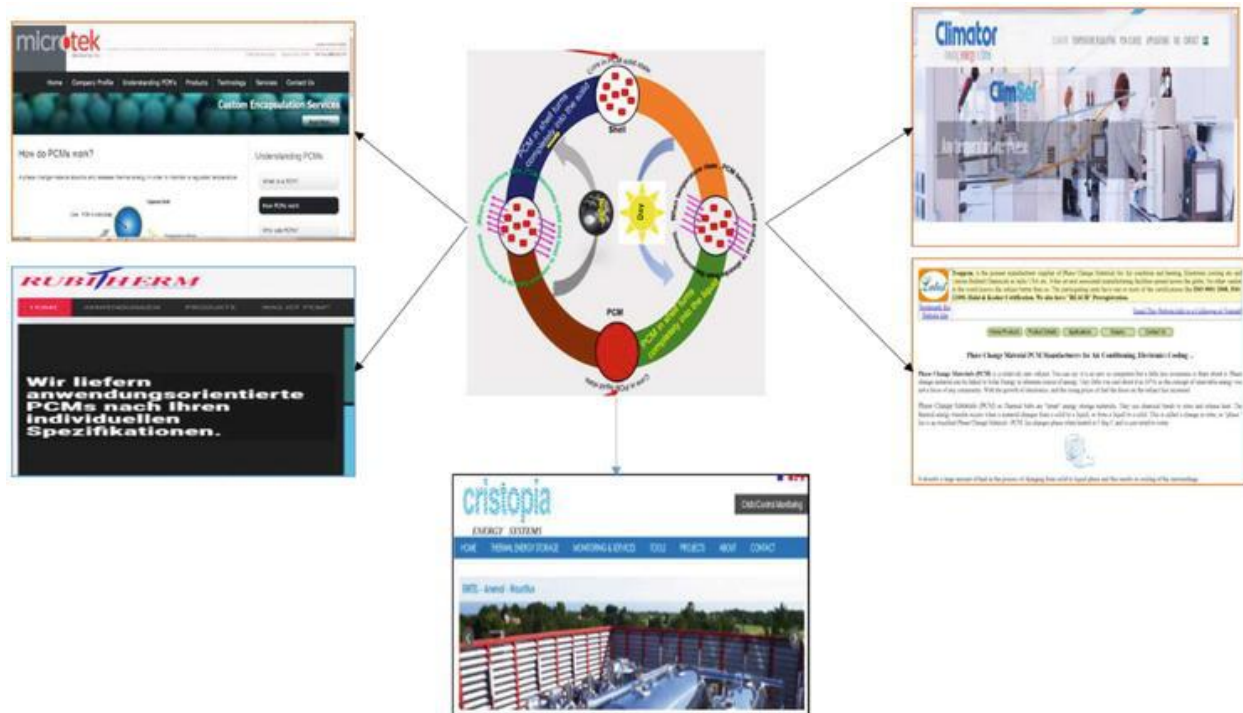
**Figure 2.** Types of thermal energy storage

**Table 1.** Differentiate between raw PCMs.

Paraffin	Fatty Acid	Eutectic mixture
<ul style="list-style-type: none"> <li>• Low thermal conductivity</li> <li>• Low latent heat of fusion at desired temperature range.</li> </ul>	<ul style="list-style-type: none"> <li>• High thermal conductivity</li> <li>• High Latent heat of fusion</li> <li>• Small Volume Change</li> </ul>	<ul style="list-style-type: none"> <li>• Eutectics have sharp melting point similar to pure substance</li> <li>• Volumetric storage density is slightly above organic compounds</li> </ul>
<b>Disadvantages</b>		
<ul style="list-style-type: none"> <li>• Low thermal Conductivity</li> <li>• Have large volume change</li> </ul>	Lack of materials with phase transition around the thermal comfort	Only limited data is available on thermo-physical properties as the use of these materials.

#### 4. ACCESSIBILITY OF PHASE CHANGE MATERIALS

1. It is available in encapsulated and unencapsulated phase change materials (PCMs) on the market. The unencapsulated PCMs, such as Indiamart and Alibaba, are manufacturing companies. Commercial encapsulated phase change materials (EPCMs) such as Microtek-BASF, Cristopia, Climator, and Rubitherm are marketed under designations such DS5001X, RT 5, and RT 25, operating within a temperature range from below ambient to above 100°C ([www.cristopia.com](http://www.cristopia.com), [www.teapcm.com](http://www.teapcm.com), [www.climator.com](http://www.climator.com), [www.rubitherm.de](http://www.rubitherm.de), [www.basf.com](http://www.basf.com)). The enclosed PCM is a minuscule particle including a core of PCMs, while the shells consist of polymers and inorganic substances (Figure 5).



**Figure 5.** Encapsulated phase change materials are commercially available (Waqas et al, 2013).

## 5. TECHNIQUES FOR INTEGRATING PHASE CHANGE MATERIALS INTO RENEWABLE ENERGY STORAGE SYSTEMS

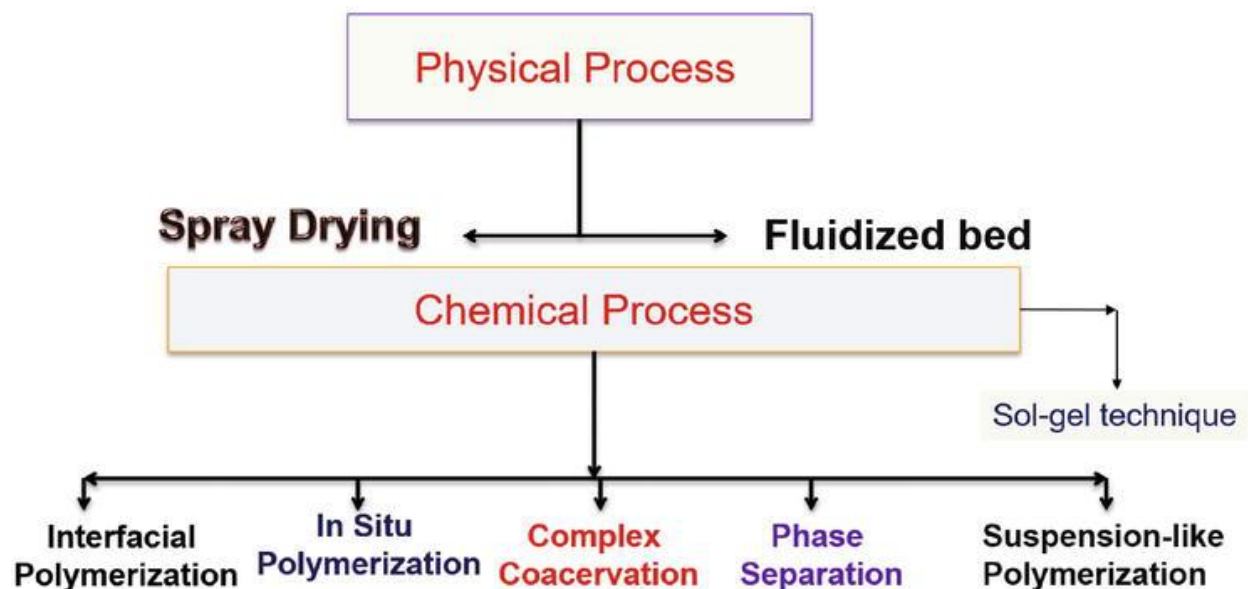
Phase Change Materials (PCMs) can be integrated through two methods: macro-encapsulation and microencapsulation for thermal storage units.

### 5.1 Macro-encapsulation

In macro-encapsulation techniques, PCM is positioned in sizes exceeding 1 mm. This technology allows for a substantial amount of PCM to be contained within a sealed vessel for later utilisation in thermal storage components (Waqas et al, 2013).. To enhance energy efficiency, researchers are experimenting with various arrangements, including raw PCM in metal balls, aluminium panels, polypropylene flat panels, and tube encapsulation. Nevertheless, metal balls and aluminium panels possess greater thermal qualities, specifically thermal conductivity, compared to polypropylene flat panels and tube encapsulation. Exergy and energy efficiency, along with the duration of hot water output, can be enhanced (Schossiq et al, 2005).

### 5.2 Microencapsulation

Encapsulation refers to a minuscule particle with a size of less than 1 mm, whereby phase change material (PCM) serves as the core, encased by an inorganic shell composed of materials such as titanium or silica. Polymers including Melamine-formaldehyde (MF), Urea-formaldehyde (UF), Polystyrene (PS), Polyurethane (PU), and Methyl methacrylate (MMA), among others. Microencapsulation of phase change materials can be achieved using two methods: the physical approach and the chemical way (Figure 6) (Borreguero et al, 2010).

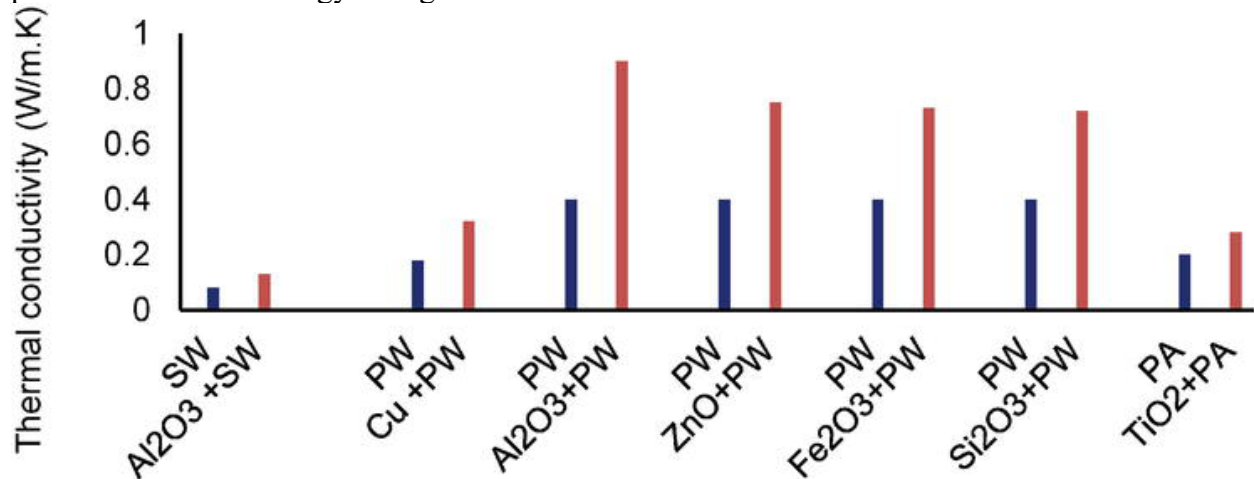


**Figure 6.** Techniques for the preparation of microencapsulation of phase change materials (PCM).

This approach regulates volume alterations during the solid-to-liquid transition, mitigates environmental interactions, and amplifies the heat transfer surface area (Fang et al, 2008). Inorganic shells can enhance the effective thermal conductivity of organic phase change materials

(PCMs). Effective thermal conductivity plays a crucial role in energy storage units (Srinivasaraonaik et al, 2020).

The use of 2–4% high thermal conductivity material into the PCM can enhance its thermal characteristics, as illustrated in Figure 7 (Tangsiriratana et al, 2019). It will enhance the performance of the energy storage unit.

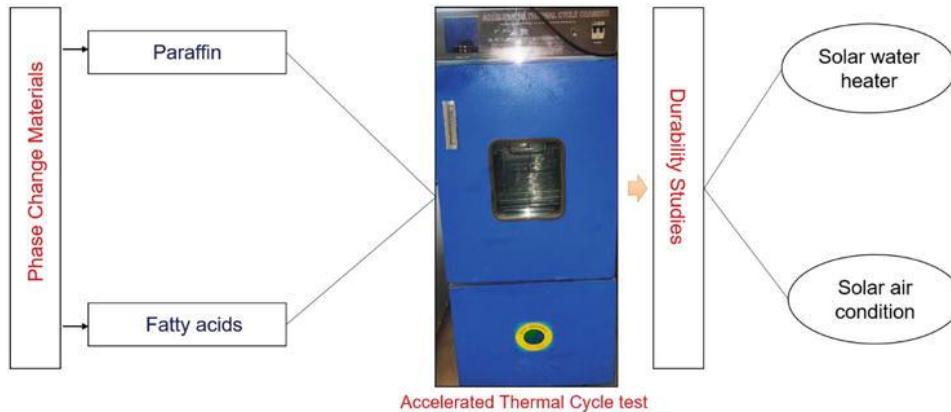


**Figure 7.** Enhancement of effective thermal conductivity of phase change materials for energy storage. \*SW: Sugar Wax, PW: Paraffin Wax, PA: Palmitic Acid.

## 6. DURABILITY OF PHASE CHANGE SUBSTANCES

An accelerated thermal cycle test is important prior to application in solar water heaters and solar air conditioners. The thermal cycle test involves heating from ambient temperature to the melting point of a phase transition until the substance is fully liquefied, followed by cooling below the melting point until it solidifies. The combined duration of the heating and cooling periods is referred to as an accelerated test. It operates once daily and illustrates the characteristics of phase change materials (Figure 8). Silakhori et al. (2013) performed accelerated testing on paraffin wax, determining its melting point and latent heat of fusion after 1000 cycles. 1.6–7% of the melting point of paraffin wax was recorded. Alkan et al. (2009) performed a thermal cycle test on microencapsulated docosane to assess its thermal stability in conjunction with polymethyl methacrylate (PMMA). No major changes occurred in crucial parameters during 5000 cycles. Ahmet Sari et al. (2009) conducted an accelerated heat cycling test on microencapsulated n-octacosane for 5000 cycles. No alterations were identified in the chemical structures of the microcapsules. Sude Ma et al. (2011) conducted thermal cycling tests of paraffin wax with PMMA for up to 1000 cycles. No alteration was detected in the thermal stability of the microcapsules.

Currently, the use of fossil fuels significantly affects the environment, prompting research in commercial refrigeration, heating and cooling systems in buildings, solar heating, electronics, textiles, and energy conservation in buildings. Phase Change Materials (PCMs) with an operating temperature range of +40°C to +80°C are utilised for solar heating, hot water generation, and electronic applications, while the range of +80°C to +1200°C is employed for absorption cooling, waste heat recovery, and concentrated solar applications.



**Figure 8.** Execution of accelerated thermal cycling test.

Yang et al. (2019) conducted an accelerated test on various fatty acids, including lauric acid, myristic acid, palmitic acid, and stearic acid, across 10,000 heat cycles. The thermal characteristics of fatty acids have remained mostly unchanged over multiple cycles. Sheili et al. (2005) conducted thermal cycle tests on a eutectic mixture of capric and lauric acid. No significant alterations in the eutectic mixture following 360 cycles. Chinnasamy V and Appukuttan S (2019) assessed the thermal characteristics of a eutectic mixture of lauric acid and myristyl alcohol over 1000 cycles. It was concluded that no alterations were seen in the thermal characteristics. Zuo et al. (2011) discovered that the eutectic mixture of lauric acid and 1-tetradecanal exhibited stable thermal characteristics up to 90 thermal cycle tests. Zhang et al. (2013) formulated a ternary fatty acid mixture of phase change materials comprising lauric acid, myristic acid, and palmitic acid. The melting point and heat of fusion remained consistent for up to 50 cycles.

## 7. PHASE CHANGE MATERIAL FOR VARIOUS APPLICATIONS IN ENERGY STORAGE UNITS

Based on the identified phase transition temperature range, they are utilised in many applications such as solar energy, buildings, and cars to reduce greenhouse gas emissions and regulate thermal conditions (Figure 9). The temperature varies from  $-20^{\circ}\text{C}$  to  $+5^{\circ}\text{C}$  for household or commercial refrigeration. The temperature range for the second phase transition, from  $+5^{\circ}\text{C}$  to  $+40^{\circ}\text{C}$ , is utilised for heating and cooling applications in buildings.

## 8. INCORPORATION OF PHASE CHANGE MATERIALS INTO SOLAR WATER HEATING SYSTEMS

Solar radiation originates from sunlight and can be captured using solar collectors. These collectors are utilised for multiple applications; one of the purposes is the generation of output hot water. The exit temperature of the hot water is contingent upon various types of collectors (Figure 10).

Typically, these sun collectors are affixed to walls for thermal regulation within structures. The thermal power output of different solar collectors can be calculated by multiplying the conversion efficiency by the intensity of solar irradiation (Douvi et al, 2021). The output of a thermal power collector can be determined using the following Equation (4).

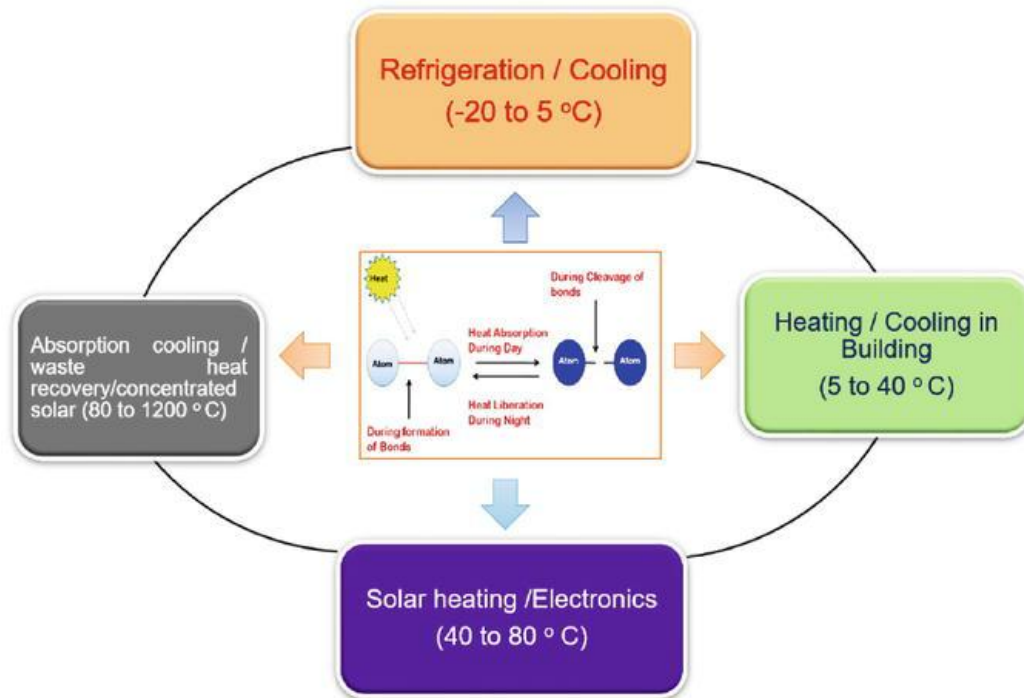


Figure 9. Phase Change Materials (PCMs) are utilised in various applications.

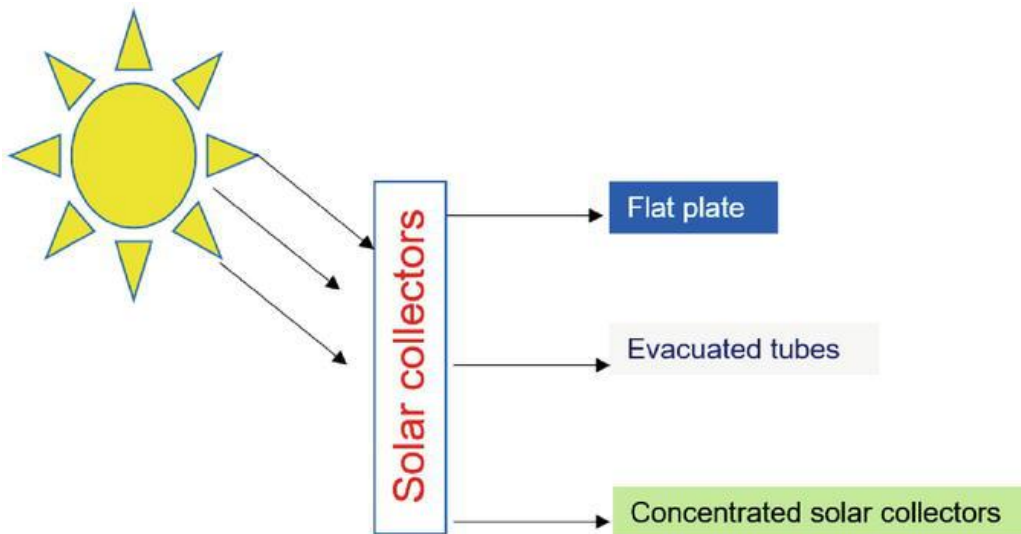


Figure 10. Diverse varieties of solar collectors.

$$Q_{KN} = \left( \eta_0 - \frac{\alpha_1(\theta_K - \theta_u) + (\theta_K - \theta_u)^2}{E} \right) \cdot E \cdot A_K = m \cdot C_p \cdot (\theta_{KO} - \theta_{KI}) \quad (5)$$

$Q_{KN}$  denotes the thermal power output of the collector (W),  $E$  represents solar irradiance intensity ( $W/m^2$ ), and  $A_K$  signifies the collector area ( $m^2$ ). Where:  $\eta_0$ : Zero-loss collector efficiency;  $\alpha_1$ :

Basic heat loss coefficient ( $\text{W/m}^2 \text{ K}$ );  $\theta_K$ : Mean collector temperature (K);  $\theta_u$ : Ambient air temperature (K).

$K_O$ : Collector outlet temperature (K),  $\theta_{KI}$ : Collector intake temperature (K),  $m$ : Heat transfer fluid mass flow rate (kg/s),  $C_p$ : Heat capacity of heat transfer fluid (J/kg K).

The flat plate solar collector is examined in detail due to its straightforward manufacturing process, cost-effectiveness, low maintenance requirements, and ease of installation. This variant of flat plate solar water heater is appropriate for urban residences (Table 2).

### **8.1 Flat Plate**

A flat plate is a form of heat exchanger utilised in solar collectors to transfer radiative energy from sunlight into thermal energy. This plate is typically utilised for applications involving low to moderate temperatures, specifically below  $80^\circ\text{C}$ . This form of collector comprises a casing, absorbers such as copper or aluminium situated within the heat exchanger due to their excellent thermal conductivity, the heat transfer fluid, and insulation materials. To enhance thermal efficiency, it is essential to minimise thermal losses and include the better thermal capabilities of phase change materials (PCM). Thermal storage materials can be incorporated within the collector or in a separate thermal storage tank. Flat plate collectors are utilised for hot water generation, space heating, and air conditioning systems [www.alternative-energy-tutorials.com, (Badiei et al, 2020)]. For solar water heating, flat-plate collectors are mounted at the optimal angle of Latitude  $+10^\circ$ . Water serves as the transport fluid in solar water heating due to its favourable thermodynamic features, including high heat capacity, high energy density, and incompressibility.

The disadvantage of using water as a transport fluid is the potential harm to the collection when it freezes in winter. The damage can be mitigated by placing the collector in areas with limited solar exposure and including antifreeze solutions to address the aforementioned issues. The common antifreeze agents are ethylene glycol or propylene glycol. These compounds are diluted with water and disposed of appropriately due to their toxicity. The longevity of antifreeze compounds is around 5 years (kalogirou et al, 2009).

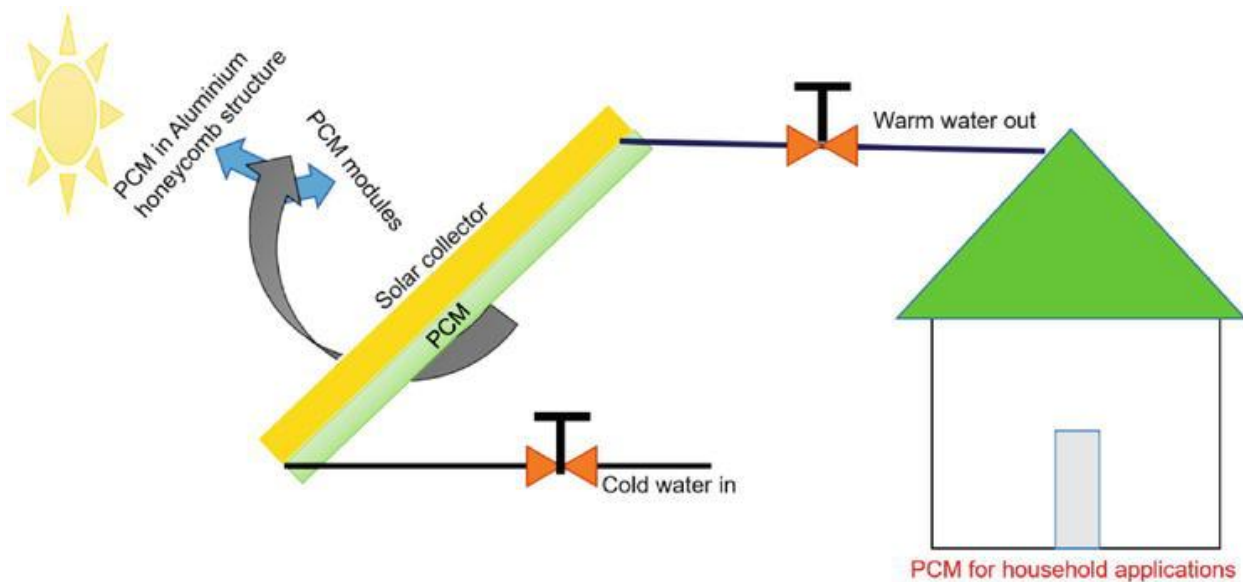
In flat plate solar water heaters, phase change materials (PCM) can be incorporated in two configurations: (i) flat plate integrated solar collectors and (ii) flat plate non-integrated solar collectors.

#### *8.1.1 Integrated Solar Collector with Flat Plate Design*

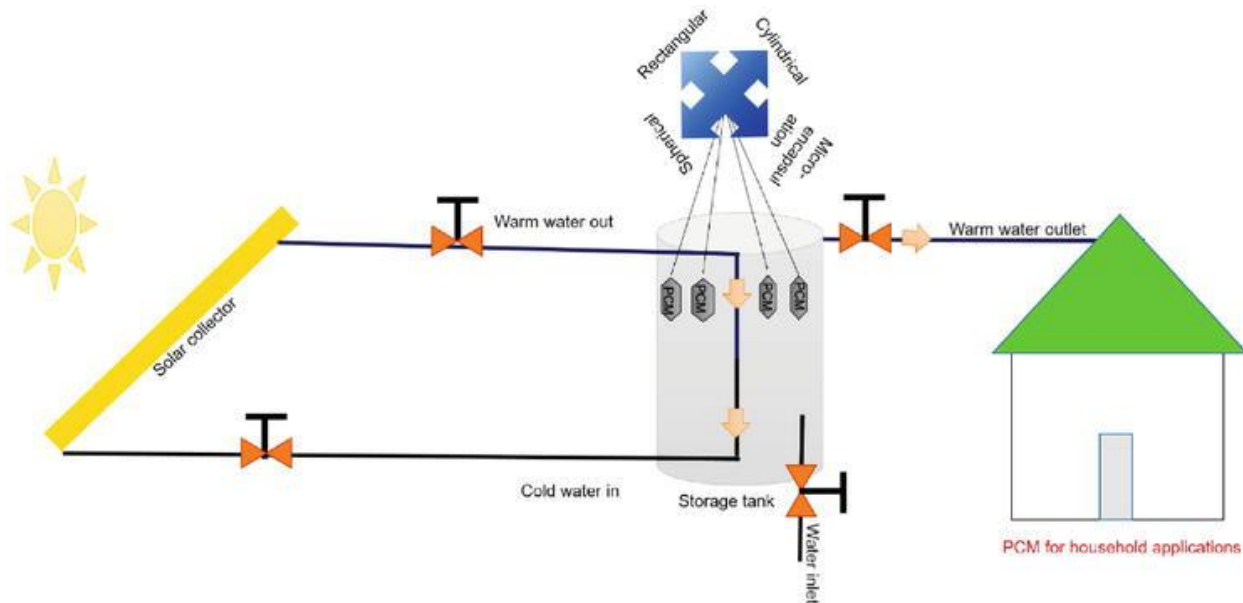
In a flat plate integrated solar collector, phase change material (PCM) can be arranged in an aluminium honeycomb configuration and PCM modules can be utilised for frost protection beneath the absorber plate (Figure 11). PCM-integrated solar collectors enhance thermal stability and prolong the availability of hot water output. Advanced insulating materials must be affixed to minimise heat loss, as failure to do so may diminish system efficiency (Abuska et al, 2019).

#### *8.1.2 Non-integrated flat plate solar collector*

Flat plate non-integrated solar collectors linked to a phase change material storage unit. The PCM storage unit is positioned above an inclined collector, adjacent to or beneath the solar collector. To prevent leakage, the phase change materials (PCMs) are enclosed in rectangular, cylindrical, and spherical containers (Figure 12; Table 3).



**Figure 11.** Phase Change Material in flat integrated solar collector.



**Figure 12.** PCM in a flat non-integrated solar collector.

Integrating a solar energy storage system into a structure may reduce the costs associated with renewable energy storage and enhance the efficiency of energy gathering. In the solar water heating method, the storage unit is filled with phase change material (PCM) to capture heat from hot water during the day. During the night, the stored energy is transferred to the warm water tank, allowing for prolonged collection of hot water Jouhara et al (2018), Taylor et al, (2017). Kulakarni and Deshmukh (2014) investigated the efficiency of a water heating system utilising paraffin with a melting point of 62°C. The efficiency of the solar water heater improved from 31.25% to 44.63%.

The storage capacity increased from 3260.4 kJ to 4656.5 kJ. Bhargava (1983) employed three distinct thermal properties of phase change materials, specifically Na<sub>2</sub>SO<sub>4</sub>·10H<sub>2</sub>O (32 °C and 251 kJ/kg), Na<sub>2</sub>HPO<sub>4</sub>·12H<sub>2</sub>O (36.1 °C and 279 kJ/kg), and P116 Wax (46.7 °C and 209 kJ/kg) were integrated into the storage unit. Assessed the system's efficiency and the duration of the outlet water temperature. As the thermal conductivity of the materials increases, the duration of elevated outlet hot water temperature during the evening hours also increases.

**Table 3.** Advantages and disadvantages of standard PCM containers for various mediums (Ling X et al, 2019).

Types	Advantages	Disadvantages
Rectangular	<ul style="list-style-type: none"> <li>• Manufacturing process is easy</li> <li>• Small occupied space</li> </ul>	<ul style="list-style-type: none"> <li>• Heat loss rate is high</li> <li>• Thermal stress concentration</li> <li>• Leakage phenomenon may exist</li> </ul>
Cylindrical	<ul style="list-style-type: none"> <li>• Fluid flow can improved</li> <li>• Rate of the PCM is high</li> </ul>	<ul style="list-style-type: none"> <li>• Manufacturing process is not easy</li> </ul>
Spherical	<ul style="list-style-type: none"> <li>• High heat transfer efficiency</li> <li>• Low heat loss rate</li> </ul>	<ul style="list-style-type: none"> <li>• Positioned in storage is complex</li> <li>• Complicated filling process of the PCM is difficult</li> </ul>
Micro-encapsulation	<ul style="list-style-type: none"> <li>• Encapsulation efficiency is high</li> <li>• Particle size is low</li> <li>• High heat transfer area is high</li> </ul>	<ul style="list-style-type: none"> <li>• Manufacturing process is tough</li> <li>• Manufacturing costs is easy</li> </ul>

*M.P.: melting point, H.F.: Heat of fusion, SA: Stearic acid, MA: Myristic acid.*

Fazilati and Alemrajabi (2013) utilised paraffin as a storage medium. The melting point and latent heat of fusion were 55°C and 187 kJ/kg, respectively. Energy and exergy efficiency improved by 39%, 16%, and 25%, respectively, along with an enhancement in the duration of warm water. Prakash et al. (1985) incorporated a phase change material layer (46.7°C and 209 kJ/kg) at the base of the water tank. They determined that it was ineffective during the phase transition from liquid to solid due to a limited heat transmission area. Kaygusuz (1995) investigated the performance of solar water utilising CaCl<sub>2</sub>·6H<sub>2</sub>O (28°C and 45 kcal/kg) as a phase change material through both experimental and theoretical methods. Hasan et al. (1995, 1994, 1994] utilised various fatty acids as phase change materials (PCMs) for domestic water heating, including myristic acid (MA), palmitic acid (PA), and stearic acid (SA). It was suggested that fatty acids with melting temperatures ranging from 50 to 70°C are the most favourable phase change materials for water heating. Most researchers examined various phase transition temperatures in solar water heater systems. According to the Cabinet of Ministers of Latvia, the permissible range for domestic hot water (DHW) is between 55 and 70°C Dzikevics M et al, (2020). The literature review presented in Table 4 indicates a phase transition temperature range of 55 to 70 °C for DHW.

**Table 4.** Literature review on phase change material flat plate solar collectors for water heating applications.

PCM	M.P (°C)	H.F (kJ/kg)	Reference
Two kinds of PCM	70	210	Zhou F et al, (2019)
Paraffin	60	213	Nallusamy et al, (2007)
Paraffin and SA	61 & 57	213 & 198	Reddy et al, (2012)
Salt hydrate	60		Dzikevics et al, (2020)
RT 60	60	144	Elbahjaoui et al, (2019)
Nano Cu-PCM (0.5 to 2%)	57.81–59.57	157.3 to 172.2	Saw C et al, (2016)
RT 65, SA, Pent glycerin	55,66,80	159,207,152	Haillet et al, (2011)
RT 65 graphite composite	65	—	Haillet et al, (2012)
Paraffin	70–80	224	Chen Z et al, (2010)
PCM1	60–62	209	Yang L et al, (2014)
Paraffin	60–70	224	Chen Z et al, (2010)
—	57.34	178.76	Shirinbakhsh et al, (2018)
MA, Paraffin, Tristearin	58, 59,56	199,189,191	Shirinbakhsh et al, (2018)
Sodium acetate tri-hydrate with graphite	60	180–200	Cabeza et al, (2006)
SA–MA (80–20%)	61–65	190.87	Mazman M et al, (2006)

In addition to the aforementioned phase change materials, several commercially available thermal storage materials within the temperature range of 55–70°C are enumerated in Zalba et al. (2003). These materials may be utilised in flat plate solar water heaters to enhance thermal efficiency, optimise thermal management, and prolong the duration of warm water availability.

## 9. CONCLUSION

Phase change materials possess high energy density and prospective use in flat plate solar collectors for the generation of hot water in urban residences. In addition to the researchers' efforts,

numerous commercially available phase change materials (PCMs) exist to enhance the efficiency of solar water systems. The thermal cycle test is crucial for assessing the durability of paraffin and fatty acids prior to their application in a system. Paraffin exhibits durability for 14 years, while fatty acid endures for 27 years. The elevated thermal conductivity of phase change materials (PCMs) prolongs the duration of hot water, whereas materials with low thermal conductivity but high latent heat of fusion can be improved by using high thermal conductivity fillers. Encapsulated phase change materials are small particles that can be readily utilised in storage tanks. Phase Change Materials (PCMs) are effectively integrated into both integrated and non-integrated flat plate solar collectors. Nonetheless, the non-integrated flat plate solar collector exhibits superior thermal efficiency compared to the integrated solar collector due to variations in heat transfer area. A variety of phase change materials, commercial methods, and designs are accessible both nationally and internationally. Cost-effective settings are selected for an efficient PCM solar water heating system.

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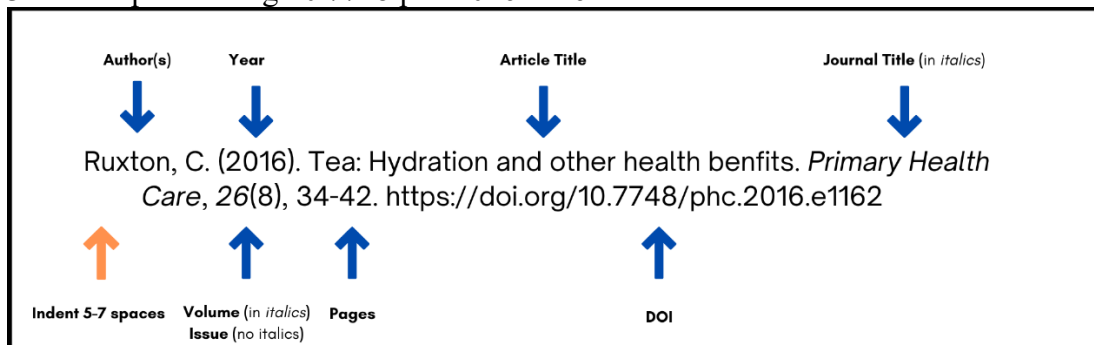
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<p><b>Journal Article: 3 to 20 authors</b></p>	<p>(Wilmott <i>et al.</i>, 2018) OR Wilmott <i>et al.</i> (2018) noted that... <b>Cite only the surname of the first author followed by <i>et al.</i> and the year.</b></p>	<p>Wilmott, C., Fraser, E., &amp; Lammes, S. (2018). 'I am he. I am he. Siri rules: work and play with the Apple Watch', <i>European Journal of Cultural Studies</i>, 21(1), 78-95836-839. <b>Provide the names of all authors in the reference list.</b></p>
<p><b>Journal Article: 21 or more authors</b></p>	<p>Research indicated that "lost sense of smell is a factor" (Khan <i>et al.</i>, 2017, p. 344).  <b>OR</b>  Khan et al. (2019) used criteria which included "reduced or lost sense of smell" (p. 344). <b>Cite only the surname of the first author followed by <i>et al.</i> and the year. Include page numbers for direct quotes.</b></p>	<p>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. <a href="https://doi.org/10.4193/Rhin19.158">https://doi.org/10.4193/Rhin19.158</a> <b>Provide the names of the first 19 authors, insert an ellipsis [...] (but no ampersand [&amp;]), then add the final author's name.</b></p>
<p><b>Journal Article from most Library databases: No DOI</b></p>	<p>Nairne and Wilkinson (2018) assert that "our relationship with ourselves is essential to how we each show up professionally" (p. 106). <b>OR</b> "Our relationship with ourselves is essential to how we each show up professionally" (Nairne &amp; Wilkinson, 2018, p. 106).</p>	<p>Nairne, D. C., &amp; Wilkinson, H. (2018). What's love got to do with it? <i>Vermont Connection</i>, 39(1), pp. 106-112.  <b>An article retrieved from most Library databases that does not have a DOI can be presented as though it were a print article.</b></p>
<p><b>Journal Article from the Cochrane Database of Systematic Reviews</b></p>	<p>The review included 78 trials employing a variety of intervention approaches (Hodder et al., 2019).</p>	<p>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., &amp; Wolfenden, L. (2019). Interventions for increasing fruit and vegetable consumption in children aged five years and</p>

	<p><b>OR</b> Hodder <i>et al.</i> (2019) identified 78 relevant trials that employed a variety of intervention approaches.</p>	<p>under. <i>Cochrane Database of Systematic Reviews</i>. <a href="https://doi.org/10.1002/14651858.CD008552.pub6">https://doi.org/10.1002/14651858.CD008552.pub6</a></p> <p><b>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.</b></p>
<p><b>Online Journal Article: No DOI (With an Article Number)</b></p>	<p>Marion <i>et al.</i> (2018) explore whether evil characters in film share .. <b>OR</b> .. including stereotypical depictions of evil characters in film (Marion <i>et al.</i>, 2018).</p>	<p>Marion, T., Reese, V., &amp; Wagner, R. F. (2018). Dermatologic features in good film characters who turn evil: The transformation. <i>Dermatology Online Journal</i>, 24(9), Article 4. <a href="https://escholarship.org/uc/item/1666h4z5">https://escholarship.org/uc/item/1666h4z5</a></p> <p><b>For an online journal article with no DOI (other than those retrieved from a Library database), provide the direct URL for the article.</b> <b>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.</b></p>
<p><b>Print Journal Article: No DOI assigned</b></p>	<p>... Aussie Rules is the people's game (Duncan, 2016)... <b>OR</b> Duncan (2016) states that a sense of belonging...</p>	<p>Duncan, S. (2016). Voices from the grandstands: The attitudes of Australian football fans towards the concept of creating, developing and binding communities. <i>Sporting Traditions</i>, 33(2), 19-40.</p> <p><b>Note: Where a print journal article has a DOI you must include it, even though you did not access the electronic version.</b></p>
<p><b>Online Journal Article: No page numbers</b></p>	<p>.. in all outcomes (Christensen <i>et al.</i>, 2019). <b>OR</b> Christensen <i>et al.</i> (2019) examine .. <b>For direct quotes of online material without pagination, name the sections and paragraph number:</b> 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).</p>	<p>Christensen, G., Dafoe, A., Miguel, E., Moore, D. A., &amp; 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. <a href="https://doi.org/10.1371/journal.pone.0225883">https://doi.org/10.1371/journal.pone.0225883</a></p>

<p><b>Secondary Sources: When you are referring to the ideas or words of an author who has been cited in another work. Also called 'secondary citation'. Only recommended where the original work cannot be obtained.</b></p>	<p>Constituting a “global movement toward a more naturalistic approach for childbirth” (Goldbas, 2012, as cited in Sullivan &amp; McGuinness, 2015, p. 20).  <b>OR</b>                  Goldbas’s overview (2012, as cited in Sullivan &amp; McGuinness, 2015) indicates...  <b>Provide names of both authors. Where the year is known for the original work, include it as well as the year of the publication you read.</b></p>	<p>Sullivan, D. H., &amp; McGuinness, C. (2015). Natural labor pain management. <i>International Journal of Childbirth Education</i>, 30(2), 20-25. <a href="https://scholarworks.waldenu.edu/sn_pubs/51/">https://scholarworks.waldenu.edu/sn_pubs/51/</a></p> <p><b>Provide the full reference for the journal article that you actually read.</b></p>
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**Using In-Text Citation**

Include an in-text citation when you refer to, summarize, paraphrase, or quote from another source. For every in-text citation in your paper, there must be a corresponding entry in your reference list. APA in-text citation style uses the author's last name and the year of publication, for example: (Field, 2005). For direct quotations, include the page number as well, for example: (Field, 2005, p. 14). For sources such as websites and e-books that have no page numbers, use a paragraph number, for example: (Field, 2005, para. 1). More information on direct quotation of sources without pagination is given on the APA Style and Grammar Guidelines web page.

**Example paragraph with in-text citation**

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**

- Derwing, T. M., Rossiter, M. J., & Munro, M. J. (2002). Teaching native speakers to listen to foreign-accented speech. *Journal of Multilingual and Multicultural Development*, 23(4), pp. 245-259.
- Thomas, H. K. (2004). *Training strategies for improving listeners' comprehension of foreign-accented speech* (Doctoral dissertation). University of Colorado, Boulder.

Cite web pages in text as you would any other source, using the author and date if known. Keep in mind that the author may be an organization rather than a person. For sources with no author, use the title in place of an author.

For sources with no date use n.d. (for no date) in place of the year: (Smith, n.d.). For more information on citations for sources with no date or other missing information see the page on missing reference information on the APA Style and Grammar Guidelines web page.

Below are examples of using in-text citation with web pages.

**Web page with author:**

Heavy social media use can be linked to depression and other mental disorders in teens (Asmelash, 2019).

*Reference entry*

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).

*Reference entry*

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>

**General Guidelines**

In-text references should immediately follow the title, word, or phrase to which they are directly relevant, rather than appearing at the end of long clauses or sentences. In-text references should always precede punctuation marks. Below are examples of using in-text citation.

*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)

**Multiple works: (separate each work with semi-colons)**

Research shows that listening to a particular accent improves comprehension of accented speech in general (Gass & Varonis, 1984; Krech Thomas, 2004).

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).

Note: For direct quotations of more than 40 words, display the quote as an indented block of text without quotation marks and include the authors’ names, year, and page number in parentheses at the end of the quote. For example:

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)

**Works by Multiple Authors**

APA style has specific rules for citing works by multiple authors. Use the following guidelines to determine how to correctly cite works by multiple authors in text. For more information on citing works by multiple authors see the APA Style and Grammar Guidelines page on in-text citation.

Note: When using multiple authors' names as part of your narrative, rather than in parentheses, always spell out the word and. For multiple authors' names within a parenthetical citation, use &.

One author: (Field, 2005)

Two authors: (Gass & Varonis, 1984)

Three or more authors: (Tremblay et al., 2010)

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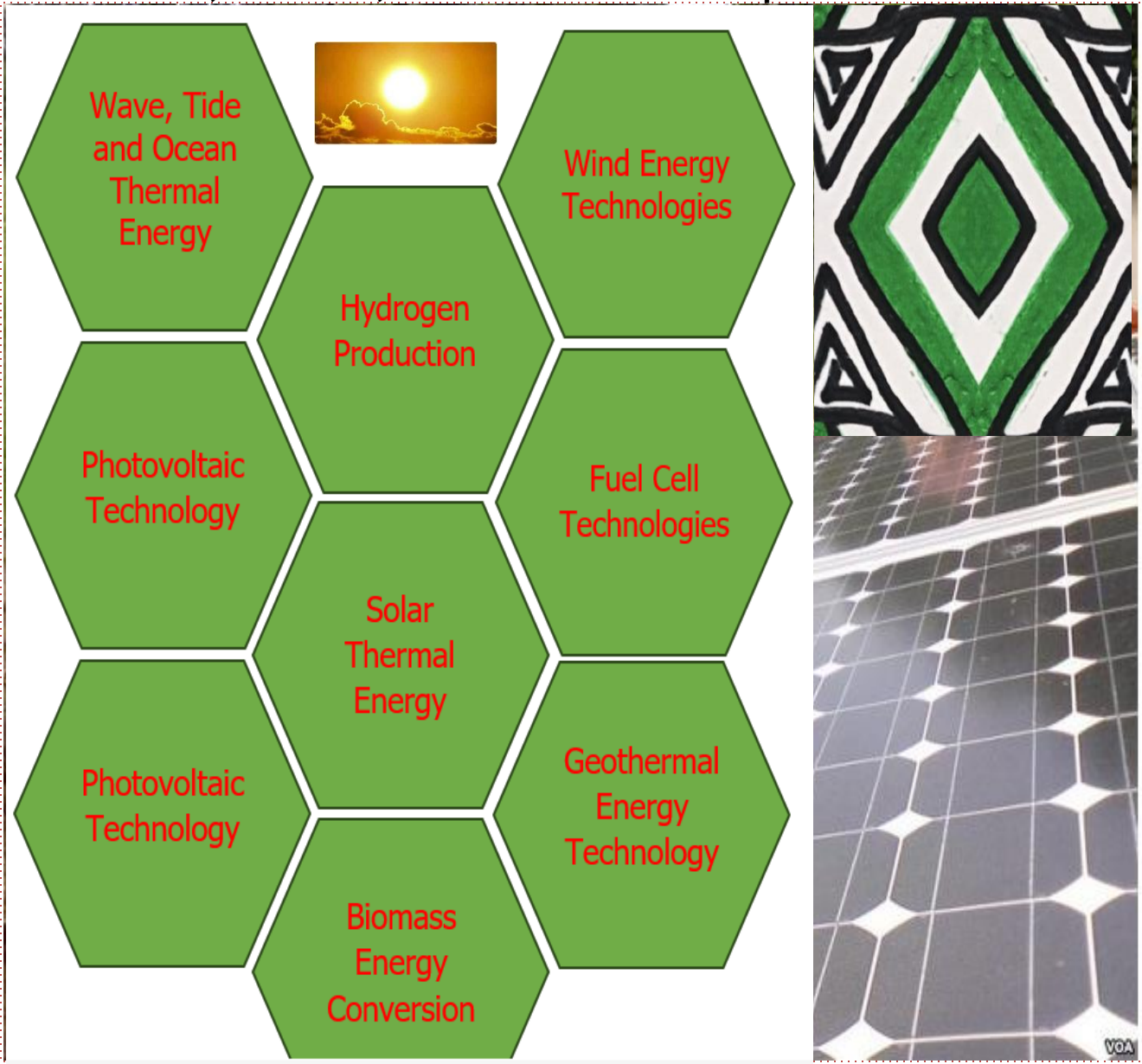
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