



SOLAR PHOTOVOLTAIC TECHNOLOGY: FUNDAMENTALS, SYSTEM DESIGN, AND DEPLOYMENT PROSPECTS IN AFRICA

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ABSTRACT

Solar photovoltaic (PV) technology has emerged as a critical component of global renewable energy transitions, with growing relevance within Africa's electricity sector. Despite historically limited deployment, projections indicate substantial expansion, with solar PV expected to contribute up to 7–8% of sub-Saharan Africa's total generation capacity by 2030 (International Energy Agency [IEA], 2014). This paper presents a comprehensive technical review of photovoltaic technology, covering fundamental operating principles, components, classifications of PV cells, and system configurations. It further examines utility-scale and rooftop PV systems, cost trends, performance metrics, environmental considerations, and socio-economic impacts. The review also evaluates design fundamentals, including solar irradiance, conversion efficiency, energy losses, degradation, and the performance ratio. Lastly, major project development requirements—ranging from feasibility studies to grid integration and economic assessment—are analysed. The study synthesises current knowledge to support planning, policy formulation, and technological deployment aimed at enhancing solar PV adoption across Africa.

1. INTRODUCTION

Solar photovoltaic (PV) systems have gained renewed global attention as countries strive to decarbonise their electricity sectors. In Africa, where energy access remains significantly constrained, PV technology presents a valuable opportunity to increase electrification, particularly in off-grid and rural regions. Historically, solar PV contributed minimally to sub-Saharan Africa's power mix; however, the Africa Energy Outlook projects its share to rise to 7–8% of generation capacity by 2030 (IEA, 2014). This transition is driven by declining PV costs, improved technological efficiency, favourable solar resources, and enhanced policy

support mechanisms.

PV technology spans a wide spectrum—from pico-solar home systems used for basic household services to large-scale utility plants exceeding 100 MW. Africa's favourable solar irradiance conditions, averaging between 2,000 and 2,500 kWh/m² annually in several regions, position the continent as one of the most promising markets for solar deployment (SBC Energy Institute, 2013). However, the effective use of PV systems requires a deep understanding of their fundamental principles, system components, design parameters, and implementation challenges.

This paper provides a technical overview of solar PV systems, encompassing their scientific basis, technological classifications, structural elements, economic feasibility, environmental implications, and socio-economic impacts. The discussion aims to inform engineers, energy planners, policymakers, and researchers seeking to advance sustainable solar deployment across Africa.

2. LITERATURE SURVEY

Solar PV technology relies on the photovoltaic effect, whereby semiconductor materials convert sunlight into electrical energy. PV modules consist of interconnected solar cells, generating direct current (DC), which may be converted into alternating current (AC) for grid applications via inverters. Commercial PV cell efficiency typically ranges from 16% to 22% for standard silicon modules, with advanced technologies achieving higher performance (Fraunhofer ISE, 2020). PV deployment in Africa has historically been limited; however, high solar resource availability and decreasing system costs have driven recent interest. The IEA (2014) emphasizes that PV's share in sub-Saharan Africa will continue to rise due to improved policies, reduced module prices, and increased experience in utility-scale installations.

Existing literature identifies four dominant PV technologies include; Crystalline silicon—monocrystalline and multicrystalline—dominates global PV markets due to high efficiency and reliability. Commercial monocrystalline cells achieve up to 22.5% efficiency, while multicrystalline modules achieve approximately 18% (Green et al., 2022).

Thin-film technologies—including CdTe, CIGS, and amorphous silicon—require less semiconductor material. Although thin-film modules typically exhibit lower efficiencies (10–13%), CdTe and CIGS technologies have achieved laboratory efficiencies exceeding 20% (NREL, 2021). Their lower production cost and superior performance under low-light conditions support their continued relevance.

CPV systems use optical lenses or mirrors to intensify sunlight onto high-efficiency multi-junction cells. Multi-junction cells have achieved efficiencies exceeding 35% (King et al., 2012), though CPV remains less common due to high cost and tracking system complexity.

Organic PV cells use polymer-based materials with low manufacturing costs. However, their commercialization is limited due to lower efficiency, shorter lifetimes, and poorer structural stability (Brabec et al., 2018). A PV system typically includes modules, mounting systems, cables, charge controllers, inverters, and battery storage for off-grid applications (EnergyPedia, 2013). System performance depends on irradiance, temperature, module mismatch, wiring resistance, and inverter efficiency. Industry studies report standard inverter efficiencies of 96–98% (Spertino et al., 2015).

Africa's high solar irradiance (up to 2,500 kWh/m² in North Africa) enhances PV performance.

However, environmental conditions such as dust and high temperatures reduce efficiency and increase PV degradation (Huld et al., 2010). Utility-scale PV plants (10–100 MW) require large land areas (1.7–5 hectares/MW) and robust grid integration studies. Power Purchase Agreements (PPAs) and Feed-in Tariffs (FiTs) remain key regulatory mechanisms supporting grid-connected projects (REN21, 2021). Rooftop PV systems, facilitated by net-metering policies, offer decentralized electricity access and reduce reliance on diesel generators—common in African commercial and residential settings.

The cost of PV systems has declined dramatically, with module prices dropping by over 80% between 2009 and 2015 (SolarServer, 2015). Energy Payback Times (EPBT) range between six months and two years, depending on technology and location (Fthenakis & Kim, 2011). PV systems emit substantially fewer greenhouse gases than fossil fuel plants and contribute positively to climate mitigation efforts. Yet, environmental concerns persist regarding battery disposal, CdTe toxicity, and water consumption for module cleaning, particularly in arid regions (Peng et al., 2013).

PV systems significantly improve living standards in rural areas, enhancing access to lighting, education, healthcare, and economic activity. Organisational models vary—from community ownership to utility-led systems—with each presenting distinct advantages and operational challenges (World Bank, 2018).

3. FUNDAMENTAL PRINCIPLES

Photovoltaic systems (PV) consist of photovoltaic modules. The fundamental item in a photovoltaic module is the solar cell, which converts light into energy. The direct current (DC) generated fluctuates continuously based on the intensity of the incoming solar radiation. The current is also dependent on incoming solar energy. A photovoltaic module comprises several solar cells interconnected to attain an elevated voltage. A module for off-grid applications is often configured for a voltage of 12 V or 24 V, utilising 36 and 72 cells in series, respectively. In grid-connected systems utilising modules with elevated voltage and alternating current (AC), an inverter is required to convert direct current (DC) into alternating current (AC). The voltage must be transformed to a minimum of 230 V, contingent upon the linked system. When cells are assembled into a module, various losses diminish the module's efficiency relative to the cell efficiency.

Photovoltaics (PV) is among the most rapidly expanding renewable energy technologies and is anticipated to significantly contribute to the future global electricity generating portfolio. Photovoltaic technology can be implemented across several sizes, ranging from an integrated solar cell in a solar lantern to a battery-operated solar system for a residence or educational institution, and even to a big grid-connected solar power plant with a capacity of several megawatts. It is essential to note that the peak solar energy received at the equator is approximately 1000 W/m² during optimal sunlight hours (see to solar irradiance). Furthermore, the optimal efficiency now attainable for commercial solar panels ranges from 16% to 22%. Consequently, one square metre of photovoltaic panel can optimally yield an electrical capacity of 220W. Enhanced efficiencies can be attained through the utilisation of many layers inside a single cell or by focussing sunlight.

4. CLASSIFICATION OF PHOTOVOLTAIC CELLS:

Numerous photovoltaic technologies have been created over the years and can be categorised as follows:

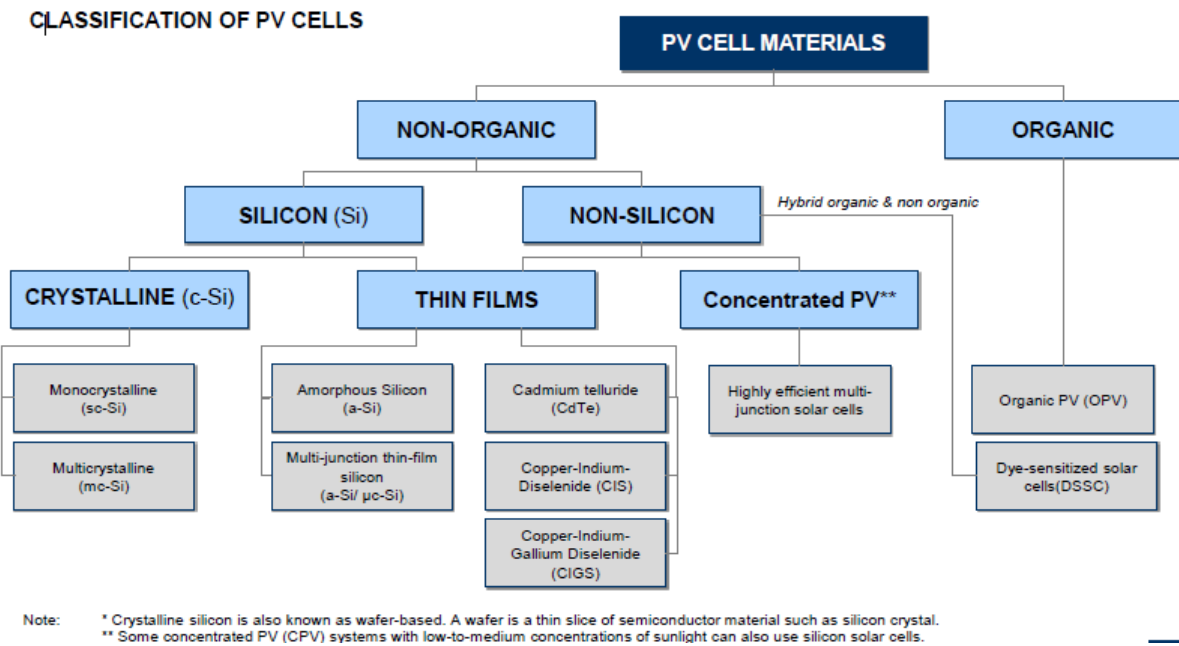


Figure 1. Classification of PV Cells:

Source: https://energypedia.info/images/4/41/SBC_Energy_Institute_Solar_PV_FactBook.pdf,

4.1 Crystalline silicon photovoltaic cells

This technique employs wafer-based crystalline silicon (c-Si) technology, specifically either single (monocrystalline, sc-Si) or multicrystalline (mc-Si). Crystalline silicon cells can be affixed to either framed or frameless panels appropriate for integration into roofs or façades. The current maximum cell efficiency for commercial monocrystalline cells is 22.5%, whereas multicrystalline cells achieve approximately 18% efficiency.

4.2 Thin-film photovoltaic cells

Thin-film technology minimises the material needed for the production of the active component in solar cells. The majority of thin-film solar cells are encapsulated between two glass panels to form a frameless module. Thin-film panels are nearly twice as heavy as crystalline silicon panels, as silicon solar panels utilise only a single pane of glass. The bulk of thin-film panels exhibit conversion efficiencies that are 2% to 3% lower than those of silicon panels. Cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (A-Si) represent three thin-film technologies. The maximum efficiency attained is approximately 20% with Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). The market share of thin-film photovoltaics constitutes around 11% of all produced photovoltaics.

5. CONCENTRATED PHOTOVOLTAIC TECHNOLOGY

Concentrating photovoltaic (CPV) systems employ optical instruments, such as lenses or mirrors, to focus direct solar radiation onto diminutive, extremely effective multi-junction solar cells. Commercial CPV modules utilising silicon-based cells exhibit efficiencies between 20% and 25%. Commercial multi-junction devices exhibit efficiencies of approximately 35%, markedly surpassing those of traditional single-junction crystalline silicon solar cells. Multi-junction solar cells comprise a series of stacked p-n junctions, each constructed from a unique combination of semiconductors, possessing varying band gaps and spectral absorption characteristics to maximise solar spectrum absorption. Multi-junction technology has lately

been commercialised and remains in limited output.

6. ORGANIC PHOTOVOLTAICS (OPV)

An organic solar cell, sometimes known as a plastic solar cell, is a variant of polymer solar cell that employs organic semiconductors. The plastic utilised in organic solar cells exhibits minimal production costs at huge volumes. Due to the adaptability of organic molecules, organic solar cells may be economically viable for photovoltaic applications. The primary drawbacks of organic photovoltaic cells include reduced efficiency, diminished stability, and inferior strength relative to inorganic photovoltaic cells. The market presently comprises just a limited number of firms. Currently, organic photovoltaics employ three principal technologies: 1. Oligomers of OPV 2. OPV Polymers 3. OPV DSSC (dye-sensitized solar cells; hybrid technology).

The details of the predominant applications for solar photovoltaic technology are as follows:

- *Utility-Scale Power Generation:* Large solar farms covering acres of land or floating on water generate power in the tens of megawatts to more than a gigawatt, feeding electricity into municipal or regional grids.
- *Residential and Commercial Buildings:* PV panels are commonly installed on rooftops to supplement power usage and reduce electricity bills. Excess energy can often be sold back to the utility grid.
- *Building-Integrated Photovoltaics (BIPV):* Solar materials are integrated into a building's structure, serving a dual purpose as architectural elements like windows, roof tiles, or cladding, as well as power generators.
- *Remote/Off-Grid Locations:* In areas where extending power lines is not cost-effective or feasible, PV systems provide stand-alone power for rural homes, telecommunications equipment, water pumps, remote health clinics, and street lights.
- *Space Applications:* From its earliest use, PV has been a primary power source for Earth-orbiting satellites, the International Space Station, and surface rovers on the Moon and Mars.
- *Transportation:* PV panels provide auxiliary power for vehicles like cars, boats, and high-altitude aircraft. They are used for onboard needs, such as charging batteries or powering specific functions.
- *Portable Electronics:* Small-scale PV cells are used in consumer products such as calculators, watches, flashlights, portable chargers for mobile devices, and integrated into items like backpacks or tents for off-grid power.
- *Agriculture:* Applications in farming include powering irrigation systems, water pumping, and agrivoltaics (combining solar generation with crop production on the same land).
- *Specialized Industrial Uses:* PV technology is used to power various stand-alone devices and tools such as temporary traffic signs, emergency phones, and for cathodic protection of pipelines to control corrosion.

Large-scale utility photovoltaic systems are engineered to deliver power to the electricity grid. The majority of contemporary solar power plants are owned by independent power producers (IPPs), however some are controlled by electric utilities. These facilities are typically constructed with capacities ranging from 10 to 100 MW and need extensive land expanses. To establish a backup generation facility, the plant is occasionally integrated with rapid-start and adequately adaptable diesel engines or open cycle gas turbines. Feed-in prices for electricity generated must range from 0.10 to 0.15 USD/kWh to achieve financial viability, contingent upon system size, solar resources, financing costs, and project hazards. The proprietor of a large-scale photovoltaic system must additionally secure a power purchase agreement (PPA)

when the energy is to be sent to the grid.



Figure 2. Large-Scale Utility-Scale Solar Energy Project

Source: <https://ratedpower.com/blog/benefits-utility-scale-solar-energy-projects>

Rooftop solar photovoltaic systems are typically linked to buildings, either incorporated into them, affixed to the roof, or situated on adjacent auxiliary structures. Building-integrated photovoltaic systems are progressively integrated into new residential and industrial structures as a primary or supplementary source of electrical energy. This market exists in numerous developing countries with elevated electricity rates, although remains unexplored in Africa. If the building cannot utilise all the energy generated by the photovoltaic system, the owner must establish an arrangement or Power Purchase arrangement (PPA) to sell the surplus energy to the grid.

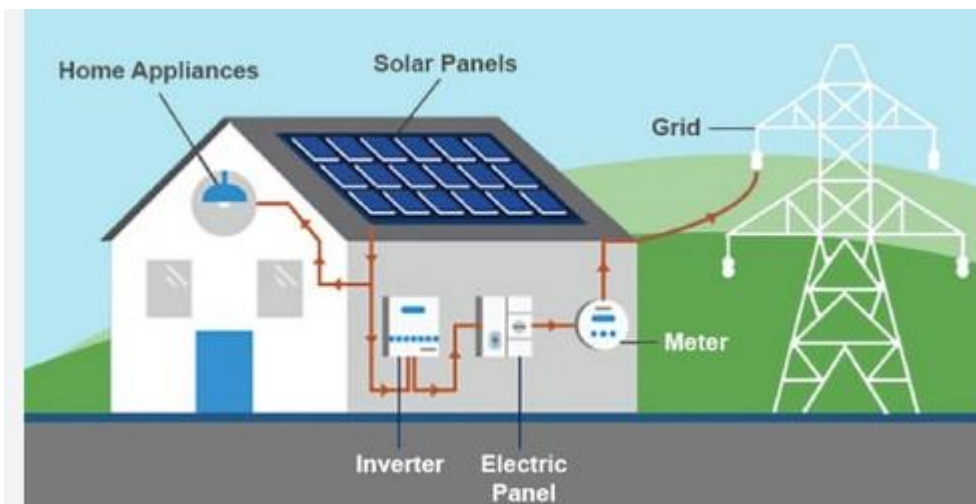


Figure 3.. Rooftop solar photovoltaic systems

Source: <https://gharpedia.com/blog/rooftop-solar-pv-system-basic-guide/>

Pico-PV and solar home systems have undergone considerable advancement in recent years, particularly in rural regions distant from the grid, integrating highly efficient lighting (predominantly LEDs) with charge controllers and effective batteries. A modest photovoltaic

module, generating only a few watts, can supply basic services such as illumination, phone charging, and radio operation. Expandable solar pico-systems have been introduced to the market. Rural households can initiate by purchasing a basic kit, subsequently augmenting it with a supplement, so enabling more lights and services to be connected, including the potential for a tiny television.



Figure 4. Pico-Scale Solar for Pico-Rural Growth in Africa
Source: <https://solarmagazine.com/pico-scale-solar-for-pico-rural-growth/>

7. OVERVIEW OF TECHNOLOGY

The primary elements of a solar photovoltaic system are:

- The photovoltaic module is a semiconductor that directly converts sunlight into electricity.
- The solar cables that connect solar modules and other electrical components within the photovoltaic system
- Mounting system - necessary for the installation of PV modules and additional components
- Batteries for electricity storage and energy provision on demand during nighttime or overcast conditions; typically utilised exclusively in stand-alone systems. Inverters are necessary to transform the direct current (DC) generated by the photovoltaic (PV) module into alternating current (AC) electricity, applicable for grid connection or a 230 V system.
- Controllers that regulate energy storage to the battery and supply power to the load

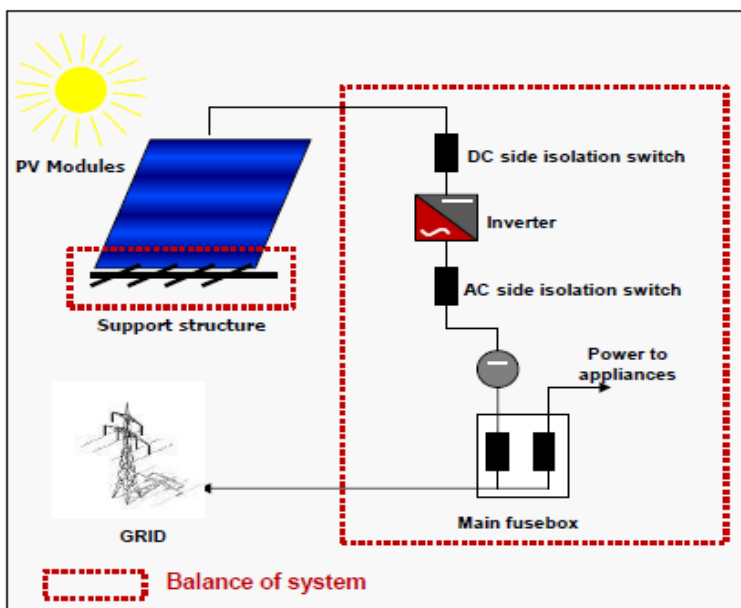


Figure 5. Diagram of a grid-tied solar energy system
Source: https://energypedia.info/images/4/41/SBC_Energy_Institute_Solar_PV_FactBook.pdf

7.1 Photovoltaic solar modules

The performance of the solar module is influenced by several factors: its dimensions (installed capacity), technological efficiency, site irradiation, surface cleanliness, power electronics (such as the engagement of a Maximum Power Point Tracking device - MPPT), and potentially a tracking system (which is uncommon in rural electrification). Given that sunny circumstances prevail in most poor nations, an installed capacity of 1 kWp (often comprising 4-6 individual modules with a cumulative area of around 8 m²) can produce over kWh yearly. In temperate, overcast climates, the modules may achieve merely 50% or less of this output. The majority of commercially available solar modules can generate electricity for a minimum of twenty years. Panel manufacturers typically provide a warranty of over 90% of rated output for the initial 10 years and over 80% for the subsequent 10 years. High-quality panels are anticipated to operate for a duration of 30 to 35 years.

The maintenance of photovoltaic modules is very straightforward, as the predominant technical issues arise from misaligned or soiled modules, which can be seen visually. In such circumstances, the captured energy diminishes, potentially disrupting the energy balance. Therefore, monitoring the surrounding area is crucial not just to prevent shadowing but also to mitigate the possibility of hot spots that could harm the generator.

Maintenance and sustainable operation are less problematic when market-based methods to photovoltaic systems are implemented, with private entities accountable for the operation of these assets and systems. Nonetheless, community or government-based management remains the prevailing reality in numerous countries. To ensure the continued operation of government/community-managed photovoltaic systems, the availability of a maintenance service provider and funds must be secured.

Solar modules may be effortlessly cleaned with water and a sponge; however, regular maintenance is still essential. This should encompass the inspection of cables and their securement, the access and examination of the junction box, and the strain relief of electrical cables. The user should conduct regular visual inspections of the wires to avert potential damage inflicted by animals. Ultimately, photovoltaic systems situated in coastal areas are susceptible to "blooming" effects on the aluminium frame due to saline air, perhaps resulting in corrosion if not managed appropriately.

7.2 Photovoltaic Cables

Solar cable is the interconnecting cable utilised in photovoltaic power generating. A solar cable connects solar modules and other electrical components within the photovoltaic system. A prevalent characteristic of the majority of solar power systems is their outdoor application, marked by elevated temperatures and intense UV radiation. Single-core cables (2.5/4.0/6.0 up to 35 mm²) are typically utilised, including a maximum allowable DC voltage of 1.8 kV and an operational temperature range of -40°C to +90°C. A three-core AC cable is utilised for grid connection with a single-phase inverter, whereas a five-core cable is employed for three-phase feed-in.

7.3 Mounting mechanisms

Ground-mounted solar power systems comprise solar panels secured by racks or frames affixed to terrestrial mounting supports. Ground-based mounting supports comprise:

- Pole mounts that are either pushed into the ground or embedded in concrete;
- Foundation supports including concrete slabs or poured footings; Ballasted foundation mounts, including concrete or steel bases, utilise weight to stabilise

the solar panel system without necessitating ground penetration. This mounting technique facilitates the decommissioning or relocation of solar panel systems without the need for ground excavation.

Roof-mounted solar power systems comprise solar panels secured by racks or frames affixed to roof-based mounting supports. Roof-mounted supports comprise:

- Pole mounts affixed directly to the roof structure, potentially utilising supplementary rails for the attachment of panel racking or frames;
- Ballasted footing mounts, including concrete or steel bases, utilise weight to stabilise the panel system without necessitating direct penetration. This mounting technique facilitates the decommissioning or relocation of solar panel systems without affecting the roof

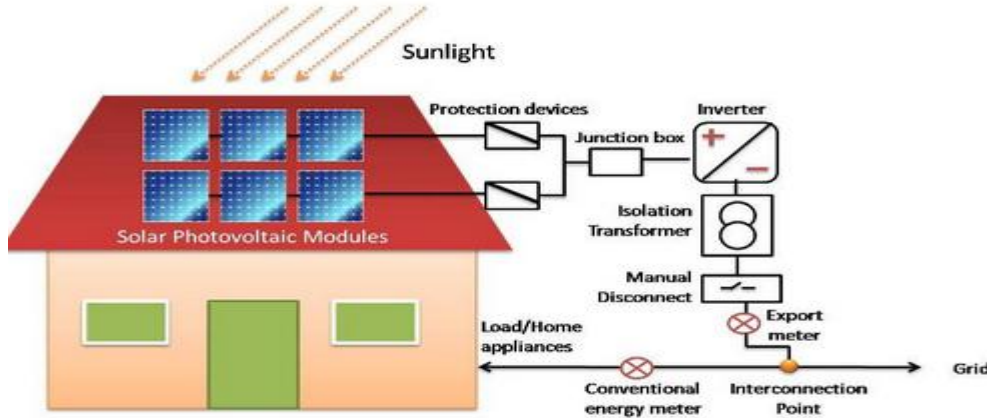


Figure 6. Roof-mounted solar power systems *Source: <https://greencleanguide.com/how-grid-interactive-roof-top-solar-pv-systems-work/>*

Fixed racks secure panels in a stationary position as the sun traverses the sky. The fixed rack determines the angle at which the panel is positioned. Tilt angles corresponding to the installation's latitude are prevalent. A minimum tilt angle is necessary for rainwater drainage in tropical climates.

Solar trackers enhance the energy output per panel, albeit at the expense of mechanical complexity and maintenance requirements. Single-axis systems follow the sun's trajectory from east to west, enhancing performance by 20 percent or more compared to fixed systems in regions with high insolation. Dual-axis trackers adjust angles along both the x and y axes, often producing approximately 8 to 10 percent more energy than single-axis trackers, contingent upon location.

7.4 Solar Charge Controller

A charge controller is essential for powering DC equipment using solar modules. The charge controller delivers a regulated DC output, stores surplus energy in a battery, and monitors battery voltage to avert undercharging or overcharging. An inverter can be linked to the output of a charge controller to power alternating current (AC) loads. A shunt charge controller or shunt regulator redirects surplus electricity to an auxiliary or "shunt" load, such as an electric water heater, when batteries reach maximum capacity.

7.5 Inverter

Inverters can be categorised into three primary types:

- Stand-alone inverters operate in isolated systems, getting their DC electricity from batteries charged by photovoltaic arrays. Numerous stand-alone inverters additionally feature built-

in battery chargers to recharge the battery from an available AC supply. Typically, devices do not connect to the electric grid and, therefore, are not mandated to possess anti-islanding protection.

- Grid-tie inverters synchronise phase with a utility-provided sine wave. Grid-tie inverters are engineered to immediately deactivate in the event of a power supply interruption, ensuring safety. They do not supply auxiliary power during utility interruptions.

Battery backup inverters are specialised inverters designed to extract electricity from a battery, regulate the battery charge through a charge controller, and transfer surplus energy to the utility grid. These inverters can provide AC power to designated loads during a utility interruption and must include anti-islanding protection.

Single-phase inverters are utilised in low to medium-sized facilities with capacities ranging from 300 Wp to 90 kWp. Multiple inverters are required to attain this amount of power capacity. The outputs of each inverter and the facility's protections are consolidated in a "Main Low Voltage Board." Some installers configure three-phase 400 Vac applications utilising single-phase inverters; this installation necessitates meticulous phase balancing. Cost is the primary factor influencing the selection of single-phase inverters over three-phase inverters. This short-term strategy neglects (i) the additional expenses associated with wiring and monitoring the AC system's balance, (ii) potential ground current through the neutral, among other issues. In the event of an inverter failure or a malfunction in one of the chains connected to the inverters, a phase imbalance arises, resulting in grid disturbances and triggering a security trip for the entire system.

Three-phase inverters are employed in medium to large-scale facilities, with capacities ranging from 5 kWp to several MWp. Various configurations of inverters are available to attain this power capacity, specifically designed for systems from 10 kWp to 1 Megawatt. Outputs and protections are centralised at the primary low voltage board when connected to the grid at low voltage. A transformer is necessary for connection to the medium voltage grid. For installations exceeding 100 kWp and reaching several megawatts, such as solar power plants, a central inverter will be employed to feed current straight into a medium voltage transformer.

7.6 Power sources

The *Lead Acid battery* consists of plates, lead, and lead oxide, along with various elements that modify density, hardness, and porosity. It contains a solution of 35% sulphuric acid and 65% water, referred to as the electrolyte, which facilitates a chemical reaction that generates electrons. During discharge, sulphur accumulates on the battery plates, and upon recharging, the sulphur reverts to the electrolyte.

Battery Maintenance: The lead battery must be cleansed with a solution of baking soda and water. Cable connections should be cleaned and secured, as battery issues frequently arise from unclean and loose connections.

Battery warranties are typically prorated based on the elapsed months relative to the warranty duration. Merely 30% of batteries sold currently attain the 48-month lifespan. Furthermore, 80% of battery failures are attributed to sulphate accumulation, which transpires when sulphur molecules in the electrolyte (battery acid) become excessively discharged, leading to a coating on the battery's lead plates.

Nickel-metal hydride battery (NiMH): This type has become prevalent in both consumer and industrial applications. It utilises a hydrogen-absorbing alloy for the negative electrode in lieu of cadmium. Following the prohibition of cadmium due to its toxicity, NiMH batteries have entirely replaced nickel-cadmium (NiCd) batteries.

Lithium-ion battery technology is employed in electric and hybrid vehicles, experiencing increased production capacity and declining costs (e.g., 3000 Euros for 10 kWh with a 10-year warranty). These batteries exhibit an excellent energy-to-mass ratio and a minimal charge retention loss during periods of inactivity. *Lithium-ion polymer batteries* are lightweight and may be manufactured in various shapes.

Table 1. Characteristics of various types of batteries

Type	Voltag	Energy density			Power	Eff.	discharg	Cycles	Lif
		MJ/kg	Wh/kg	Wh/l					
Lead-acid	2.1	0.11-	30-40	60-75	180	70-92	3-4	500-800	20
NiMH	1.2	0.11-	30-80	140-	250-	66	30	500-	
Li ion	3.6	0.58	150-	250-	1800	80-90%	5-10	1200	10
Li-	3.7	0.47-	130-	300	3000+	99.8%	2.8-5.05	500-	2-3

8. FUNDAMENTAL COMPONENTS OF DESIGN

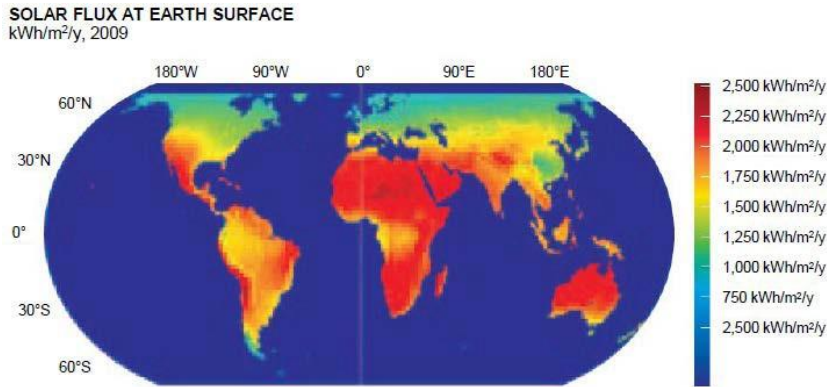
The efficacy of a photovoltaic (PV) plant is contingent upon climatic conditions, the utilised equipment, and the system configuration. The principal energy input is solar irradiance and global irradiation on the plane of the solar modules, which comprises both direct and diffuse radiation. A crucial factor influencing system output is the conversion efficiency of the solar modules, which is particularly dependent on the type of solar cells employed, ranging from 14% to 19% for commercially available crystalline solar cells.

8.1 Solar Irradiance

Solar irradiance refers to the radiation emitted by the sun that passes through Earth's atmosphere. It is quantified by satellites positioned near the outer layer of the atmosphere, known as the solar constant, which measures 1361 W/m². Solar radiation from the sun is diminished by the atmosphere before it reaches the ground, which can be categorised into two primary types: clear and cloudy. Due to scattering and absorption within the atmosphere, the final irradiance value that reaches the ground and can be harnessed by photovoltaic modules is approximately 1000 W/m². This represents the sun's power.

Direct normal irradiation (DNI) refers to the quantity of solar radiation incident per unit area on a surface maintained perpendicular to the direct rays from the sun at its present position in the sky. The cumulative daily solar irradiation per square meter represents the total energy received daily (kWh/m²). Additionally, monthly or annual totals can be quantified or simulated using various programs. The overall power sum over a specified duration equates to total energy, defined as energy *power x time*.

Photovoltaic (PV) modules are systems that convert incoming light into electricity. Africa possesses significant solar energy potential, with most regions receiving over 320 days of bright sunlight annually and experiencing global irradiation levels nearing 2,000 kWh per square meter (kWh/m²), which is double the average in Germany. The optimal solar resources are concentrated in the Sahara, North Africa, and certain areas of Southern Africa, where irradiation levels approach 2,500 kWh/m². Central and West Africa generally have lower irradiance levels, particularly near the Gulf of Guinea.



Source: Breyer and Schmidt (2010); IEA (2011), "Solar Energy Perspectives"
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Figure 7. Solar Flux at earth surface.

Source: https://energypedia.info/images/4/41/SBC_Energy_Institute_Solar_PV_FactBook.pdf

8.2 Conversion Efficiency – Loss Diagram

Various factors, including light absorption losses, mismatch, cable voltage drop, conversion efficiencies, temperature effects, and other parasitic losses, contribute to the discrepancies between Direct Normal Irradiance (DNI) and the actual AC power supplied to the grid. The loss diagram offers a concise overview of the quality of a photovoltaic (PV) system design by pinpointing the primary sources of losses, as depicted in the diagram below.

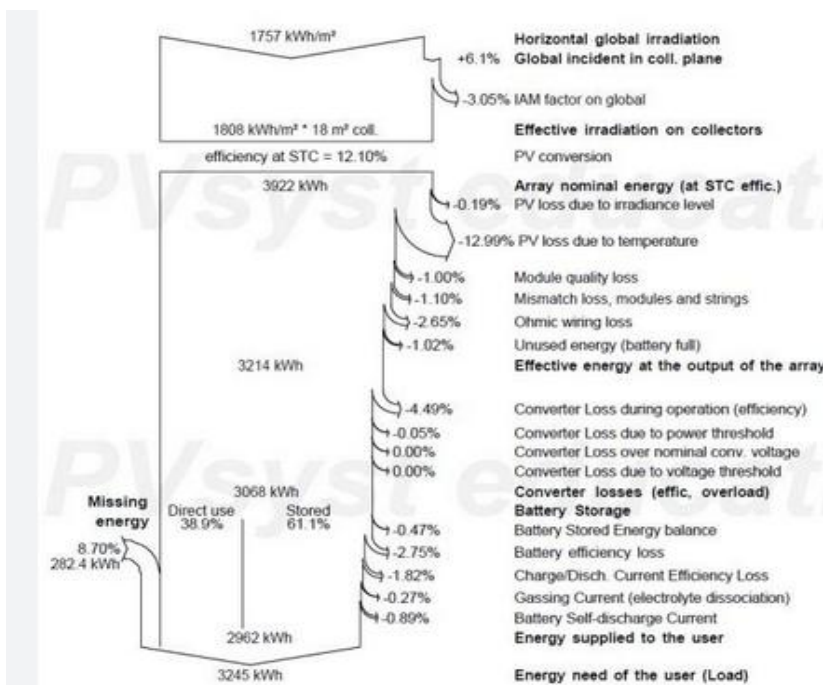


Figure 8. loss diagram of solar PV system Fig.12 represents the loss diagram of solar PV system.

Source:

https://www.researchgate.net/publication/341238063_Design_and_Performance_evaluation_of_Proposed_2_kW_Solar_PV_Rooftop_on_Grid_System_in_Odisha_using_PVsyst/figures?lo=1

8.3 Loss diagram generated using PV-SYST software

Each loss is characterised as a percentage of the preceding energy quantity. Consequently, the percentage values are not additive; when aggregating the losses, the total percentage does not equal the sum of the individual values.

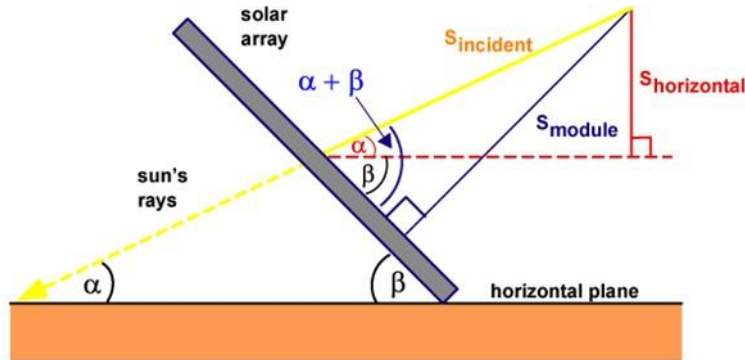


Figure 9. Global incidence on the collector plane.

Source: <http://www.pveducation.org/pvcdrom/properties-of-sunlight/solar-radiation-on-tilted-surface>

The global incidence on the collector plane results from the transposition of irradiance from horizontal ("S horizontal" as indicated in the solar irradiance atlas) to the plane of the array ("S module" at an angle β relative to the horizontal).

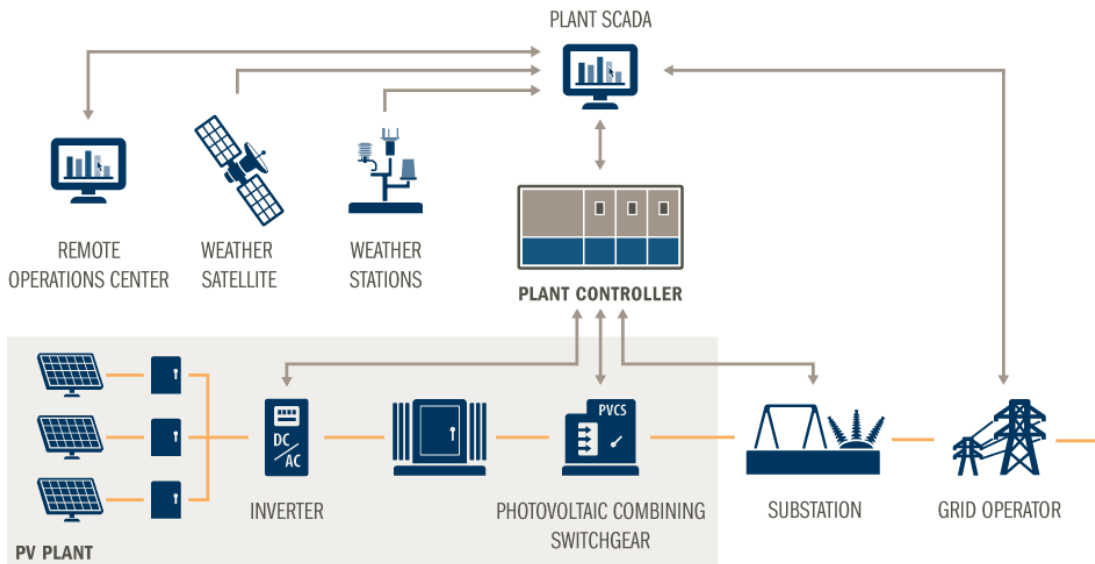


Figure 10. Technologies and capabilities/grid integration for Solar Systems

Source: <http://www.firstsolar.com/en/technologies-and-capabilities/grid-integration>

The incidence effect (or IAM, for "Incidence Angle Modifier") refers to the reduction of irradiance that actually reaches the surface of the photovoltaic cells beneath the protective layer (typically glass with an antireflective coating) compared to irradiance at normal incidence, attributable to increased reflections at higher incidence angles.

The Air Mass represents the distance light travels through the atmosphere, normalised to the minimum distance (when the sun is directly overhead). It quantifies the attenuation of light intensity as it traverses the atmosphere, being absorbed by air and particulate matter. The Air Mass is defined as:

$$AM = 1/\cos(\theta)$$

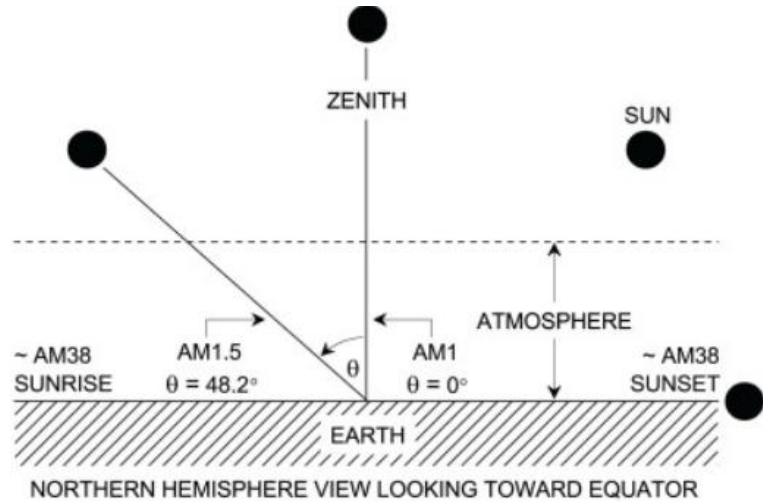


Figure 11. Solar geometry: Angle of Incidence (AOI), Zenith Angle (z), and air mass (SO:ZO).
Source: <https://www.sciencedirect.com/topics/engineering/air-mass>

Here, θ denotes the angle from the vertical (zenith angle). When the sun is positioned directly overhead, the Air Mass equals 1. *Source: <http://www.pveducation.org/pvcdrom/properties-of-sunlight/air-mass>*.

8.4 Photovoltaic cell conversion efficiency

A crucial factor influencing the system's output is the conversion efficiency of the solar modules, which is particularly contingent upon the type of solar cells employed. Upon commissioning, the normalised solar cell efficiencies at Nominal Operating Cell Temperature (NOCT) of 46°C are as follows:

- Monocrystalline or Polycrystalline silicon cells 12.5%-15%
- Thin film cells: 9.5% - 10%
- Multi-junction cells: 33%-35%

8.5 Photovoltaic conversion loss attributable to temperature

The normal test circumstances stipulate a cell temperature of 25°C ; nevertheless, modules typically operate at significantly elevated temperatures. For crystalline silicon solar modules exclusively, the direct current power output diminishes by 0.7-0.9% for each degree Celsius over 25°C .

8.6 Photovoltaic conversion loss attributable to module mismatch

The total power output of the photovoltaic array is consistently inferior to the aggregate maximum output of the individual modules. This phenomenon arises primarily because, within a series of modules (or cells), the lowest current dictates the current of the entire series. This discrepancy, termed "Mismatch loss," results from minor variations (statistical distribution of cell parameters) in performance among modules and leads to a minimum power loss of 2% in the system.

8.7 Photovoltaic conversion loss attributable to wire resistance

Power is also dissipated due to resistance in the system wiring. These losses should be minimised, however maintaining them below 1% is challenging. A pragmatic reduction factor for these losses is 99% or negative 1%.

8.8 Photovoltaic conversion loss attributable to the inverter

The direct current generated by the solar module must be converted into alternating current using an inverter, resulting in some power loss during the conversion. Contemporary inverters exhibit peak efficiencies ranging from 96% to 98%, as stated by manufacturers.

8.9 Photovoltaic degradation attributable to module ageing

The median degradation rate is approximately 0.5% per annum, with modules produced post-2000 exhibiting a markedly reduced degradation rate, resulting in a mere 12% loss of output performance over 25 years. Conversely, a system utilising modules that degrade at 4% per annum will experience a 64% reduction in output during the same timeframe. Numerous panel manufacturers provide a performance guarantee, generally ensuring 90% output after ten years and 80% after 25 years. The output of all panels is typically guaranteed within a tolerance of plus or minus 3% during the initial year of operation.

8.10 Performance Ratio (PR)

The performance ratio (PR) measures the losses between the nominal DC output of solar modules under standardised test conditions and the actual AC power supplied to the grid. This encompasses various factors, including light absorption losses, mismatch, cabling, and inverter efficiency. In contemporary solar installations, the performance ratio is generally expected to be around 80%.

8.11 Utility-Scale Photovoltaic Systems



Figure 12. Utility-Scale Photovoltaic Systems Source: energy.mit.edu/news/solar-photovoltaics-the-benefits-outweigh-the-costs/

A substantial photovoltaic power facility comprises:

- Photovoltaic array composed of discrete modules
- Direct Current (DC) bus

- Direct Current to Alternating Current power inverters
- Alternating current voltage electrical systems
- Communication and botanical surveillance system

Photovoltaic modules are affixed to support structures and interconnected to provide power output to the electronic power conditioning subsystem. Solar modules generate direct current (DC) electricity; therefore, solar power plants require conversion equipment to transform this into alternating current (AC), the form of electricity transmitted by the grid. This conversion is accomplished by grid-connected inverters, which are engineered to automatically shut down in the event of a power supply interruption for safety purposes.

The efficacy of a photovoltaic plant is contingent upon climatic circumstances, utilised equipment, and system architecture. The principal energy input is the global sun irradiance incident on the solar panels, which comprises both direct and diffuse radiation components.

The advancement of large-scale utility photovoltaic (PV) systems is associated with the policies and regulations governing the electricity sector, particularly concerning renewable energy generation, both centralised and decentralised. The Feed-in Tariff policy has been implemented by several nations. A Power Purchase Agreement (PPA) is invariably required for all large-scale PV installations.

In large-scale photovoltaic power plants, it is essential to assess grid stability and the reliability of power flows during a grid connection study. The power plant may complicate voltage regulation along the feeders. Sophisticated power electronics can enable the power plant to actively participate in voltage regulation. Additionally, the power plant may interfere with system protection schemes, complicating fault detection and coordination of protective devices. Innovative sensors, communication technologies, and management systems will facilitate the restoration of system reliability.

8.12 Rooftop Solar Photovoltaics

A rooftop photovoltaic power station, or rooftop PV system, is a solar energy system with electricity-generating modules installed on the roofs of residential or commercial structures. Its components comprise photovoltaic modules, mounting systems, cables, solar inverters, and various electrical accessories. These rooftop systems are smaller than ground-mounted photovoltaic power stations, which operate in the megawatt range. Typically, rooftop PV systems on residential buildings have capacities of approximately 5 to 20 kilowatts (kW), whereas those on commercial buildings can exceed 100 kilowatts.

The advancement of rooftop photovoltaic systems is associated with net metering policies and regulations. Net metering permits grid-connected electricity consumers who generate their own power to "bank" or "store" excess electricity during periods of overproduction (such as solar energy during peak daylight hours) and to offset their grid consumption with this stored electricity at other times (for instance, during nighttime,

morning, and evening hours). Net metering is typically, though not exclusively, applied to small-scale generators utilising renewable energy sources.

9. STANDARD BENCHMARKS

9.1 Cost Trends of Photovoltaic Systems

The expense of a photovoltaic (PV) system is contingent upon its market, although patterns are globally applicable. For instance, the overall cost of a PV system in Germany diminished from \$5.43/Wp in 2009 to \$2.40/Wp in 2015, indicating a reduction of around 60% over six years.

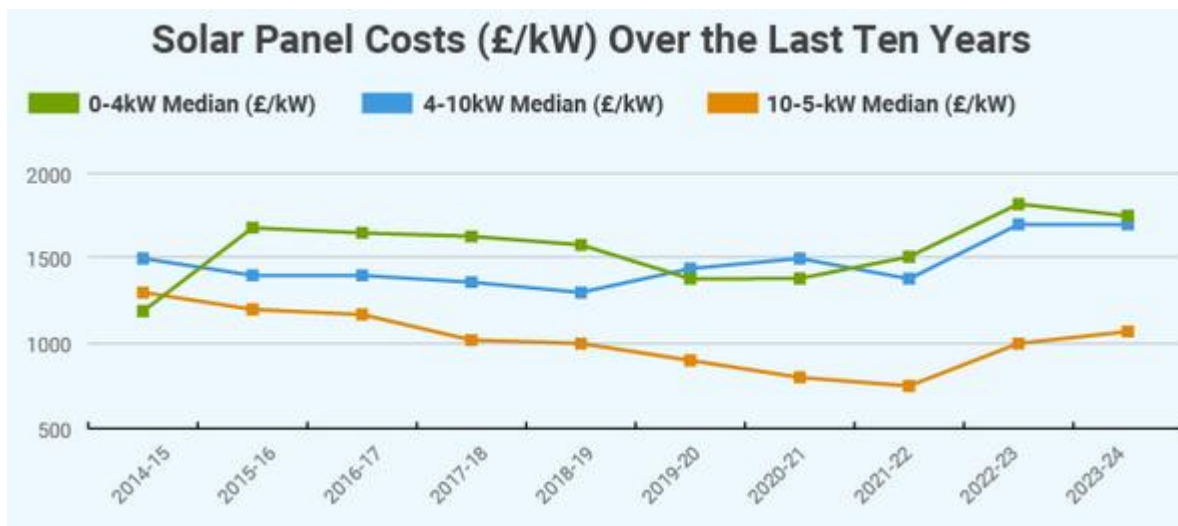


Figure 13. Cost of Solar Panels Source: <https://www.greenmatch.co.uk/blog/decrease-in-solar-costs>

- Over the past decade, the cost of solar panels has decreased globally by 90%, now being under \$0.20 (£0.15) per watt.
- Conversion efficiency improved from 1–2% to 22% within the past century, reducing manufacturing and installation costs.
- Incentives like the Feed-in Tariff and Smart Export Guarantee have driven adoption and cost reduction.
- Prices are expected to drop to \$0.097 (£0.075) per watt by 2030, further accelerating adoption.

Solar panels, once an expensive product, are now the cheapest they have ever been, with prices declining every year worldwide. This dramatic decline is a huge win for sustainability. As solar panel costs become more accessible, homeowners and businesses are now able to implement greener energy solutions. This shift helps reduce carbon emissions and promotes a more sustainable future.

In the last decade, solar panel costs have fallen by **90% worldwide**, according to [Our World Data](https://ourworldindata.org/data-insights/solar-panel-prices-have-fallen-by-around-20-every-time-global-capacity-doubled). (<https://ourworldindata.org/data-insights/solar-panel-prices-have-fallen-by-around-20-every-time-global-capacity-doubled>)

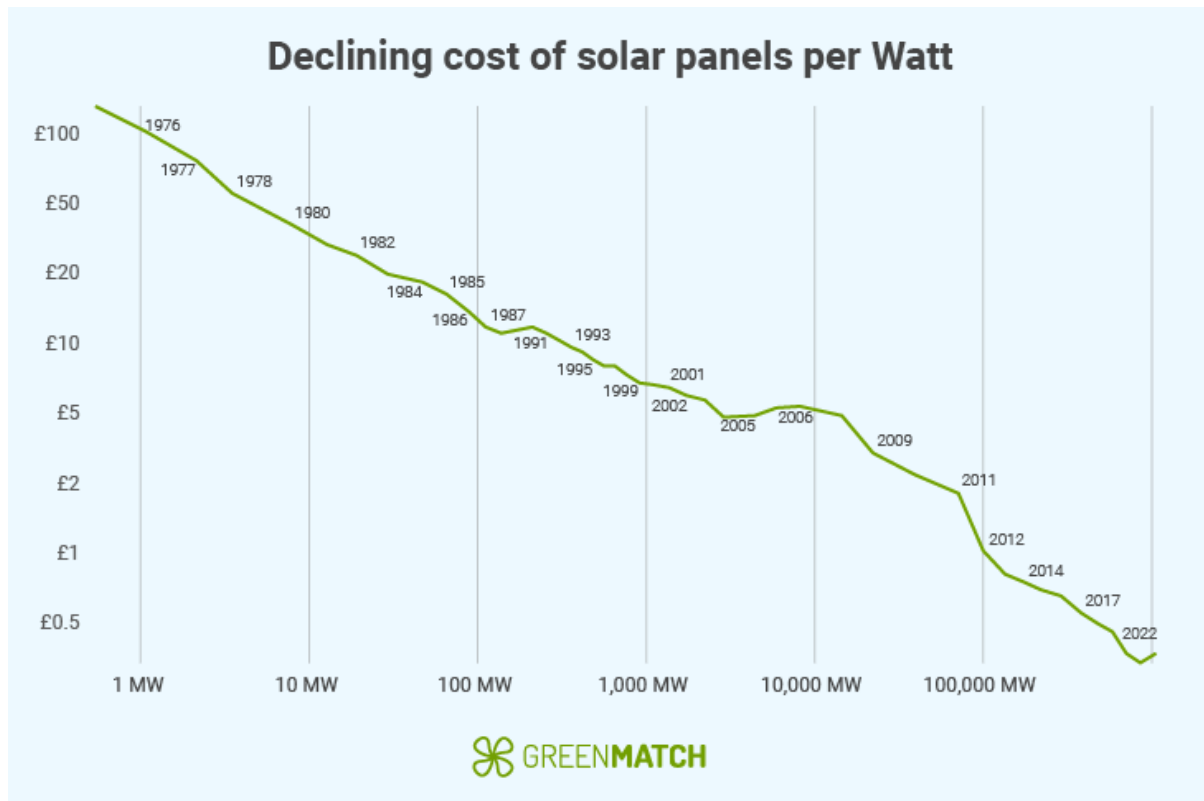


Figure 14. Declining cost of Solar panels:

Source: <https://www.greenmatch.co.uk/blog/decrease-in-solar-costs>

To accelerate sustainable practices and encourage more people and governments to adopt solar energy, it is important to forecast the future costs of solar panels. Forecasting future costs relies on looking at its decline and the factors that contribute to it. In this article, we delve into the breakdown of the cost evolution of solar panels, the reasons for their decline, and the future outlook of solar panel prices.

9.2 Economic and ecological dimensions

9.2.1 Financial considerations

Solar photovoltaic plants are capital-intensive infrastructures characterised by low operation and maintenance expenses in the absence of batteries. The comprehensive cost distribution is as follows:

- Capital expenditure consisting of:
 - Supply and installation of photovoltaic modules and support structures.
 - Supply and installation of inverter equipment.
 - Battery banks (optional).
 - Generator set (optional),
 - Supply and installation of electrical instruments and controls (I&C).
 - Project indirect expenses, charges, and contingency provisions, and Owner's expenses (excluding project finance expenses).
- Operational and Maintenance expenses (O&M) encompassing:
 - Fixed O&M expenses, which do not fluctuate greatly with generation, indicate that operating labour costs are often minimal, as plants are automated and maintain a

- limited number of staff on-site during standard operations.
- Variable O&M costs are production-related expenses that fluctuate with electrical generation.
- Significant maintenance expenses (The repair and replacement of massive electro-mechanical equipment necessitate qualified personnel and the importation of specialised equipment and spare parts that are frequently unavailable in the African market.)

The subsequent table delineates the standard allocation of capital expenditures for the principal components of a large-scale Solar PV facility. The predominant portion of the cost is ascribed to the PV modules, highlighting the significant sensitivity associated with this expense.

Table 2. Capital expenditures for the 5 MW solar power plant.

Category	Amount
Land plot acquisition	EUR 250,000
Grid connection fee	EUR 190,000
Main project design	EUR 50,000
Groundworks	EUR 210,000
Concrete works	EUR 170,000
Metal substructure with installation	EUR 375,000
Solar modules and inverters with installation	EUR 1,650,000
Substation with construction works	EUR 350,000
Electric and other cables	EUR 280,000
Supervision works	EUR 60,000
Other construction works	EUR 180,000
Overheads (10%)	EUR 376,500
Total	EUR 4,141,500
Total per kW	EUR 828.30

The primary benefit of solar photovoltaic technology is the substantial reduction of variable costs, particularly fuel expenses. Due to the standardised design and mass production of solar modules, their manufacturing costs can be maintained at acceptable levels.

Most commercially available solar modules are engineered to produce electricity for a minimum of twenty years. Manufacturers typically provide a quality guarantee of over 90% of rated output for the initial 10 years and over 80% for the subsequent 10 years. Nevertheless, under moderate climate conditions, modules may be anticipated to have a lifespan of up to 30 years.

The energy payback time (EPBT) for photovoltaic (PV) modules refers to the duration required to generate the total energy consumed throughout their life cycles. Presently, the EPBT ranges from six months to two years, contingent upon location, solar irradiation, and technology. Solar PV systems emit minimal greenhouse gases during operation. Moreover, a solar photovoltaic power plant will supplant fossil fuels utilised in traditional power generation, either diminishing import reliance or freeing fossil resources for alternative applications. Under climate change regulations, the abatement effect on greenhouse gas emissions can be monetised through carbon credits, so generating additional revenue.

Solar photovoltaic power is typically regarded as a "must-run" energy source. A solar photovoltaic plant lacks energy storage capacity and hence cannot synchronise power producing output with consumer demand. Solar photovoltaic power is frequently seen as a "non-firm" energy source. It is unfeasible to guarantee a consistent power generation output for an extended duration. The power purchase agreement (PPA) stipulates that generation may be below expectations for a specified duration, providing the plant can thereafter compensate for the generation shortfall. This represents a conventional "non-firm" agreement, which is the normal arrangement for solar photovoltaic generating facilities. Solar photovoltaic plants typically produce greater energy output in the dry season compared to the wet season. The solar radiation pattern and corresponding electricity generation are somewhat predictable in the short term (day-ahead scheduling).

9.2.2 Ecological consequences

Upon the completion of a photovoltaic (PV) facility, the project generates no direct waste and exhibits significantly lower carbon dioxide (CO₂) emissions compared to fossil fuel power plants. The sole carbon footprint arises from the manufacturing of equipment and the construction of the plant. The total land area required for ground-mounted systems varies based on technology, site topography, maintenance choices, and geographical location (latitude). Large-scale PV systems necessitate approximately 1.7 to 5 hectares per megawatt (MW). Certain thin-film PV cells, such as Cadmium Telluride (CdTe), contain hazardous materials. Improper handling and disposal of these substances could pose serious environmental or public health risks. Nonetheless, manufacturers possess a substantial financial incentive to ensure the recycling of these valuable and often scarce materials rather than their disposal.

Pico-PV systems, including solar lanterns and solar home systems, frequently utilise batteries containing hazardous materials. Many developing nations lack sufficient battery collection and recycling initiatives. This issue necessitates attention, as it may undermine the advantages provided by these systems. Additionally, large-scale PV installations in arid regions require water for panel cleaning to remove dust.

9.2.3 Societal influence

Solar photovoltaic systems exert a substantial beneficial influence, particularly in rural regions distant from the electrical grid. The provision of electricity enhances the quality of life, and when capacity is adequate for lighting and powering educational institutions, healthcare facilities, and public utilities, social services experience significant enhancement. Solar PV systems bolster energy security, and individual solar installations render users resilient to fluctuations in fuel prices, fuel shortages, power outages, or inflation. For large-scale photovoltaic installations, land management considerations, particularly regarding ownership, must be addressed.

10. ORGANISATIONAL FRAMEWORKS

The various organisational models presently employed globally can be encapsulated in Table 3.

Table 3. Various Solar organisational models presently employed globally

Model	ownership	Control	Operation maintenance	Finance	Utility's role
G0.0	End-user	End-user	End-user	End-user	Passive
G1.0	Third-party	End-user	Third-party	Third-	Facilitator
G2.1	Third-party or end-user	Third-party or end-user	Third-party	Third-party	Facilitator and passive PV services buyer
G2.2	Third-party or end-user	Utility	Third-party	Third-party	Facilitator and active PV services buyer
G2.3	Utility	Utility	Utility	Utility	System integrator and services seller

11. RESEARCH AND ENQUIRIES

The technical analyses required for the development of a solar power plant project encompass:

- Sun irradiation research: compilation of satellite data, consultation with local meteorological authorities if available, on-site measurement and analysis of sun irradiation, precipitation, wind velocity, and temperature.
- Evaluation of the legal framework: which legal structure is most suitable, and what are the local regulations pertaining to contracts, land ownership, electricity transactions, warranties, etc., as well as the enforcement of contracts.
- Geological assessment: soil characteristics beneath primary civil engineering projects.
- Geographic assessment: topographical survey, site plan with contour lines, project layout incorporating contour lines, evaluation of infrastructural facilities.
- Design of solar photovoltaic systems: arrangement of PV modules, configurations in parallel and series, angle of the photovoltaic array, spacing of the photovoltaic array, and calculation of the efficiency of grid-connected PV systems.
- Power analysis: assessment of power generation and the plant's influence on the current grid system.
- Design of civil infrastructure: powerhouse (plan, section), access roads.
- Design of electrical apparatus and specification data sheet: inverters, electrical control systems and SCADA (Supervisory Control and Data Acquisition), lightning protection and grounding, relay protection and metering, electric single line diagram (including protection and metering), 33 kV switchyard (plan and section), medium voltage (MV) and low voltage (LV) cubicles, generator transformer and protection, station transformer, medium voltage line, metering system, and station auxiliaries.
- Operational instruments: inventory of essential spare components, inventory of tools.

12. Environmental and Social Impact Assessment (ESIA)

Economic analysis: cost estimates (bill of materials and cost data sheet), operational and maintenance expenses, applicable feed-in tariff and anticipated revenue, cost-benefit analysis.

Risk assessment: primary risks and mitigation strategies.

12.1 Duration

The execution (up to the initiation of operations) of a solar PV project is contingent upon its scale. A standard sequence of steps can be broadly outlined in Table 4.

Table 4. Standard sequence of steps for Solar Projects

Step/Phase	Duration range	Main Activities/Method
Identification	1 to 3 months	On site reconnaissance, desk studies, data analysis
Pre-feasibility study	3 to 6 months	On site surveys, preliminary design and computations
Feasibility study (Including ESIA studies)	6 to 24 months	On site surveys, in situ tests, economic analysis, cost estimates, design development
Detailed design	6 to 12 months	Computations, modeling, bills of quantities
Tender documentation	3 to 6 months	Bidding documents, contracts models
Tendering/Bidding period (till award of)	3 to 6 months	Contractual and administrative documentation package
Mobilization of financing	9 to 18 months	Commitments of lenders and financing agreements
Implementation	6 to 18 months	Construction, commissioning

The durations presented in the aforementioned table are merely indicative. Generally, for a completely new project, the timeline from identification to commissioning may range from 2 years to over 5 years in adverse scenarios where phases are not completed promptly, contingent upon the project's size and complexity.

12.2 Essential enquiries

Market assessment

- Is there a national policy objective for the proportion of solar energy in the electricity mix and the corresponding strategy? Is it being executed?
- Does the policy promote the hybridisation of diesel generators for isolated grids?

Project advancement

- Is the project developer dependable? (Adequate technical proficiency in photovoltaic farms, financial stability, experience in the country of operation, access to funding)?
- Will the national regulations pertaining to this investment type be enforced?

Fiscal examination

- Is the feed-in tariff satisfactory for both parties (project developer and national utility) regarding price, duration, and terms (take or pay on committed energy production, pay per committed available capacity)?
- Is there a reduced tariff for the seller's delivery that falls below the short-term commitment (under generation) and for the buyer's acceptance that is less than the deemed generated energy (under acceptance)?
- Is the maintenance component of the tariff adjusted to labour and photovoltaic equipment costs?
- What effect would the feed-in tariff have on the financial status of the national utility and the electricity costs for end consumers?
- What is the national grid's capacity to accommodate the additional electricity generated?
- Is the photovoltaic project the most cost-effective choice for electricity generation?
- What will be the operational expenses of the photovoltaic power plant, including maintenance costs?

Economic assessment

- What is the project's effect on economic activities and income generation?
- What is the anticipated societal impact on the beneficiary population on education and

health?

- What effect will this photovoltaic power facility have on state finances?
- What are the potential uses for the electrical surplus (market sales, utilisation in industrial processes such as desalination, etc.)?

Organisations and business frameworks

- Is the selected business model suitable for the country?

Technology

- What will be the effect of the new photovoltaic power plant on the grid?
- What actions would be implemented to ensure grid stability regarding voltage and frequency?
- Does it align with essential technological benchmarks? (Anticipated production per kWp installed)?
- Is the land necessary for the construction of the plant accessible, and what will be the implications for the environment and agricultural outputs?
- What measures would be used to guarantee after-sales servicing and maintenance?
- Is sufficient water accessible on the location for cleaning the PV modules? Is the chosen location adequately illuminated without any shade?

13. CONCLUSION

Solar photovoltaic technology represents a transformative and increasingly viable solution for addressing Africa's persistent electricity challenges. With abundant solar resources, declining PV system costs, and expanding technological options, African countries can accelerate energy access, support economic development, and reduce greenhouse gas emissions through strategic PV deployment. The literature shows that PV system performance depends not only on solar irradiance but also on appropriate design, choice of technology, and quality of system components. Utility-scale and rooftop PV systems present complementary pathways to expanding solar generation, supported by strong policy frameworks such as FiTs and net metering.

However, achieving sustainable PV integration requires addressing environmental considerations, ensuring battery recycling, conducting robust feasibility studies, and strengthening institutional capacity. As Africa navigates its energy transition, comprehensive planning and adherence to international technical standards will be essential. Solar PV offers a reliable, scalable, and low-carbon energy solution capable of driving long-term socio-economic progress.

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Conflicts of Interest

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

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