https://doi.org/10.52131/jee.2024.0502.0046

*i*RASD Journal of Energy & Environment

Volume 5, Number 2, 2024, Pages 76 - 100

Journal Homepage:
https://journals.internationalrasd.org/index.php/jee

*i*RASD JOURNAL OF ENERGY & ENVIRONMENT
INTERNATIONAL RESEARCH ASSOCIATION FOR SUSTAINABLE DEVELOPMENT

An Overview on Photovoltaic System

Osama Saad Hamad Saleh[1], Kalad Saad Hmad Saleh[2], Izzeldin Idris Abdallah[3]

[1] Department of Electrical Engineering, Faculty of Engineering Sciences, Bright Star University, El Brega, Libya. Email: osamasaadhamad79@yahoo.com
[2] Sirte Company for the Production and Processing of Oil and Gas, Marsa Al Brega, Ajdabiya, Libya. Email: hammad762008@yahoo.com
[3] Department of Renewable Energy Engineering, College of Energy Technologies, Jikharra, Libya. Email: eng.izzeldin@gmail.com

ARTICLE INFO

Article History:

Received:	August	25, 2024
Revised:	November	23, 2024
Accepted:	November	25, 2024
Available Online:	December	04, 2024

Keywords:
Overview
Photovoltaic System
Electricity
Renewable
Energy

JEL Classification Codes:
Q20, Q4

Funding:
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

Photovoltaic (PV) cells are a renewable energy source that is safe for the environment; they capture and convert sunlight into electrical power using solar arrays or modules. The PV panels generate electrical energy from solar radiation, and in this PV panel-based energy conversion system, maximum power point tracking (MPPT) is a crucial component. Partial shading conditions result in a decrease in the PV systems' energy output, and this phenomenon is encountered in all types of PV systems. Hence, an in-depth description of the PV system is provided in this study.

Corresponding Author's Email: osamasaadhamad79@yahoo.com

Citation: Saleh, O. S. H., Saleh, K. S. H., & Abdallah, I. I. (2024). An Overview on Photovoltaic System. *IRASD Journal of Energy & Environment*, *5*(2), 76–100. https://doi.org/10.52131/jee.2024.0502.0046

1. Introduction

Photovoltaic (PV) cells utilize solar modules or arrays to capture sunlight and convert it into electrical energy, offering a sustainable renewable energy solution. The essential elements of a photovoltaic panel-based energy conversion system comprise the photovoltaic array (which captures and converts solar energy into electrical energy), a DC-DC converter for increasing low DC voltages to high DC voltages, an inverter for converting DC voltage into AC voltage, a maximum power point tracking (MPPT) digital controller for regulating the converter's operation, and an AC filter that mitigates harmonics (voltage and current) produced by the inverter (Liu, Wu, & Cheung, 2004). According to the materials used, the various types of PV panels on the market are categorized as illustrated in Figure (1). However, silicon-based solar cells continue to lead the market due to their advanced technology and high-efficiency requirements (Pandey et al., 2016).

Crystalline semiconductors, such as Si and GaAs, outperform the other options available on the market. However, less pure materials provide less effective but still affordable solar cells. As a result, scientists worldwide are investigating other, more effective ways to use solar cells to generate power (Pandey et al., 2016).

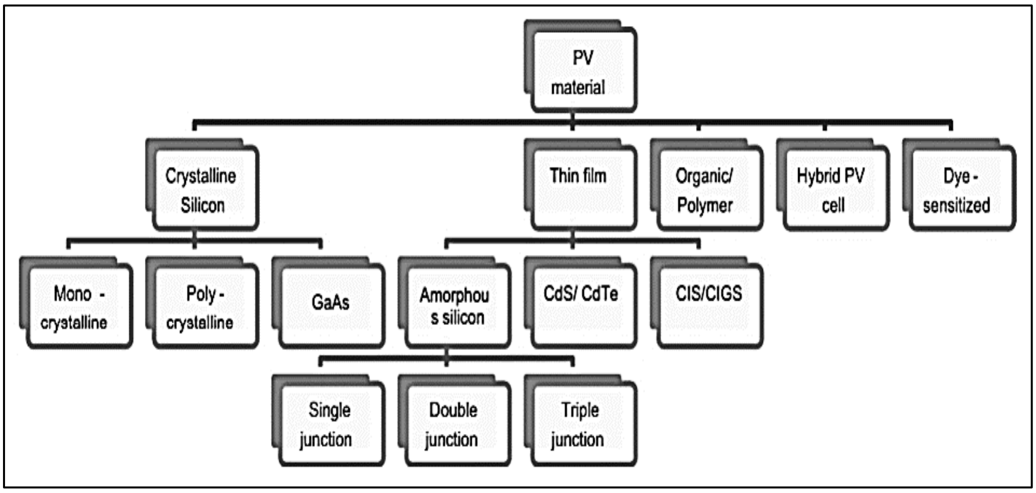


Figure 1: Materials Used for PV Panels
Source: Pandey et al. (2016)

1.1. Photoelectric Effect

When electromagnetic radiation, such as light or high-energy particles, collides with a material, the outcome is the emission of electrons, which are referred to as photoelectrons. This phenomenon is referred to as the photoelectric effect. Research has been undertaken on this topic in quantum chemistry and condensed matter physics to elucidate the properties of atoms, molecules, and solids. Many metals that release negative electricity when exposed to UV light have drawn increased interest from the public, as has the impact of UV light on gas ionization (Liu et al., 2004; Lopez-Varo et al., 2016; Pandey, Jena, & Qian, 2023).

1.1.1. Explanation of the Photoelectric Effect

Electrons, or photoelectrons emitted by a metal surface upon light interaction, are ordinary. The photoelectric effect (PE) describes this phenomenon. The kinetic energy and photoelectrons emitted from a surface are both affected by the strength of the incident light. When light strikes a metallic surface, it triggers the release of photoelectrons, a phenomenon known as photoemission. The ability of surface electrons in a metal to absorb light energy and use it to offset the attractive forces that bind them to the metallic nuclei is the source of potential energy. According to Singh and Chaturvedi (2016), the photoelectric action causes photoelectron emission, as seen in Figure 2.

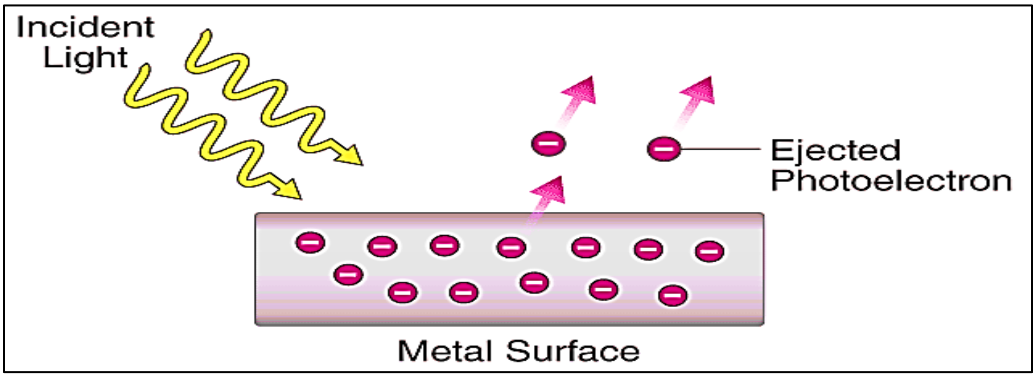


Figure 2: The Photoelectric Effect's Resultant Photoelectronic Emission

Light's particulate nature, which allows it to be seen as a stream of electromagnetic energy particles, can be used to explain the photoelectric effect even if it may not be described by thinking of light as a wave; we refer to these light particles as photons. Planck's equation, which relates a photon's energy to the light's frequency, is expressed as follows (Lopez-Varo et al., 2016; Sohoni, 2012).

$$E = hf_L \quad (1)$$
$$f_L = c/\lambda \quad (2)$$

Where:

E = photon's energy;
h = Planck's constant;
fL = light's frequency;
c = speed of light (in a vacuum);
λ = light's wavelength.

This means that light travels at different frequencies, carrying photons with different energies. For instance, blue light has a higher frequency than red light due to its significantly shorter wavelength. So, compared to red light, blue light has more incredible energy in its photons. In Einstein's theory of the photoelectric effect (PE), the photon's energy is equal to the sum of the energy needed to free an electron and its kinetic energy (Singh & Chaturvedi, 2016).

$$hf_L = W + E \quad (3)$$

Where:

W = a work function;
E = ejected electron's maximum kinetic energy $(= 1/2\ \lbrack mf_L \rbrack^2 h)$.

1.1.2. Relationship between the Energy of Photon and the Kinetic Energy

According to Bertoluzzi et al. (2015), the relationship between the incident photon's energy and the produced photoelectron's kinetic energy can be expressed as follows:

$$E\_photon = \Phi + E\_electron$$
$$\Rightarrow\ hf_L = h\ \lbrack(f_L)\rbrack_{th} + 1/2\ m_e\ \lbrack f_L \rbrack^2 \quad (4)$$

Where:

$Ephoton\ =\ the\ incident\ photon's\ energy\ (=\ hf_L)$,
$\Phi\ =\ metal\ surface's\ threshold\ energy\ (=\ h\ \lbrack(f_L)\rbrack_{th})$,
$Eelectron\ =\ photoelectron's\ kinetic\ energy\ (=\ 1/2\ m_e\ \lbrack f_L \rbrack^2)\ and\ m_e\ =\ electron's\ mass, which\ is\ =\ 9.1 * 10 - 31\ kg$.

No photoelectrons will be emitted if the photon's energy is below the threshold energy. Therefore, if $f_L < (f_L)_{th}$, the PE will not occur. Photoelectrons will be emitted if the photon's frequency is precisely equal to the threshold frequency $(f_L = (f_L)_{th})$, but their kinetic energy (KE) will be 0. Figure (3) provides an instance of how the incident light's frequency affects the photoelectron's kinetic energy (Singh & Chaturvedi, 2016).

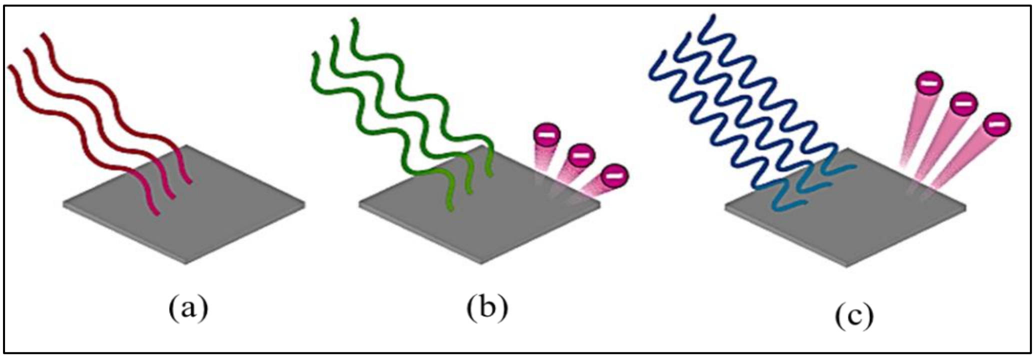


Figure 3: The Emission of Photoelectrons

As shown in Figure 3, the photoelectric effect occurs when the light depicted in Figure 3 (a) impinges upon the metallic surface, as its frequency is below the metal's threshold frequency. Instead, photoelectrons are released when the light in Figure 3 (b) strikes the surface of the metal. Furthermore, the PE also occurs when the metallic surface in Figure 3 (c) is struck by light. Blue light, however, generates photoelectrons with significantly greater kinetic energy than green light due to its higher frequency.

It is crucial to remember that different metals have different threshold energies. This is because various metals have different attractive forces that hold electrons to them. It should be mentioned that non-metals can also experience PE, but their threshold frequencies are often quite high (Singh & Chaturvedi, 2016). The photoelectric effect is the term used to describe the phenomenon of electrons being excited by photons that strike a solid metal surface. Singh and Chaturvedi (2016) were the first to elucidate the photoelectric effect by utilizing resonator entropy as a function of energy. The aggregate entropy for the system of N resonators was defined as (Pandey et al., 2023):

$$S_N = NS \tag{5}$$

Where:

S = single resonator's average entropy; the total entropy SN is dependent on the level of disorder in the distribution of total energy UN across the individual resonators.

1.1.3. The Dynamical Process of the Photoelectric Effect

An example of a physical event is the photoelectric effect, which necessitates a fundamental description through a dynamic method that amalgamates physics and mathematics. A considerable quantity of electrons is seen within and on the surface of the metal plate depicted in Figure 3.4 below. A photon or particle p generates radiation by a series of subtle oscillations in a solid metallic plate. A photoelectron is released upon collision with an electron on the metal plate (Pandey et al., 2023).

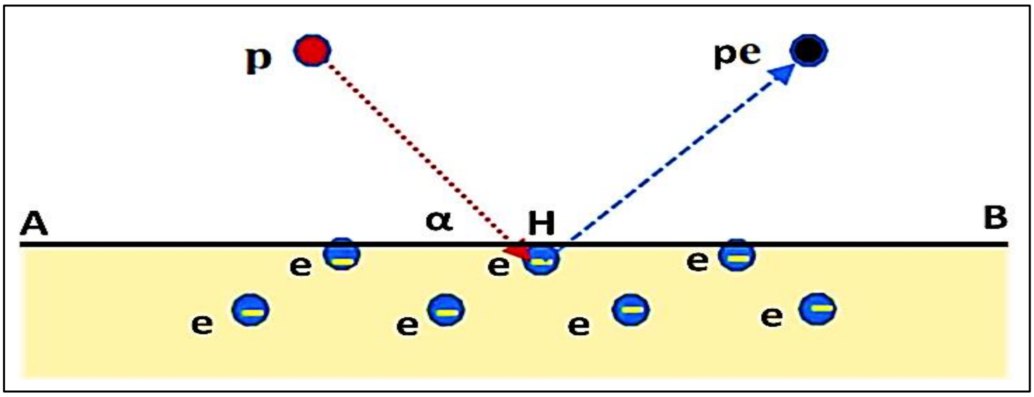


Figure 4: The Emission of A Photoelectron *Pe* From A Metal Plate

Wave-particle duality is a feature of energetic particle propagation. An electron e is traveling rapidly around its nucleus, as seen in Figure (5). At point H, an electron interacts with a particle p that is traveling along a wave-like trajectory. The angle of collision is θ. Initially, we confirm the presence of a high-energy particle p with mass mp rather than focus on the mass of the photon's incident on the surface of the metal plate. Several electrons may surround an atomic nucleus. Atoms in different substances differ from one another, and the number of electrons carried by various atoms varies. Figure (5) illustrates that an electron's mass is me and a particle's mass is mp. When they collide at point H, they all exhibit specific centripetal forces, Fp & Fe, given as:

$$F_p = \frac{m_p}{r_p} v_p^2 n_p, \tag{6}$$

$$F_e = \frac{m_e}{r_e} v_e^2 n_e \tag{7}$$

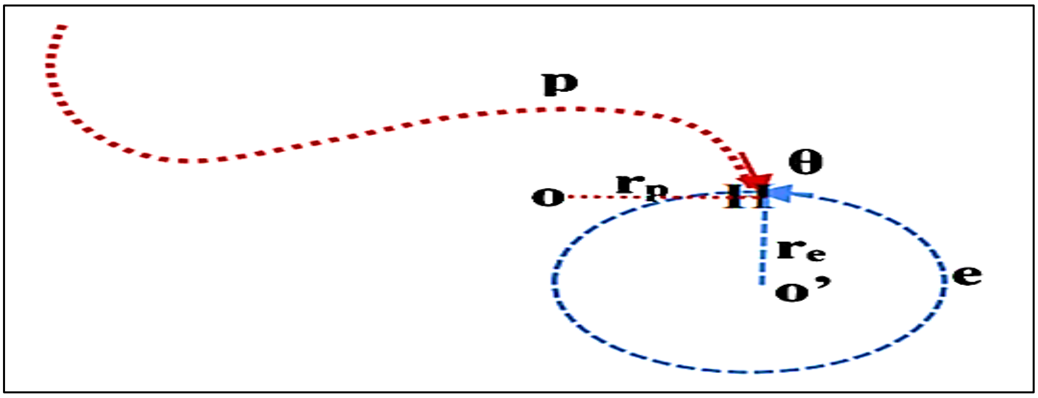
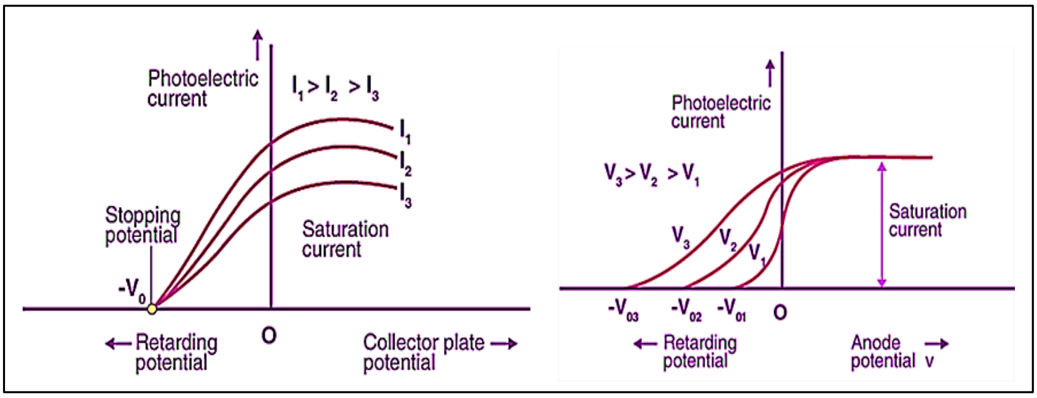


Figure 5: A Photon *P* And Electron *E* Collide at Point *H* With a Collision Angle *Θ* Between Them

1.1.4. Different Graphs of the Photoelectric Equation

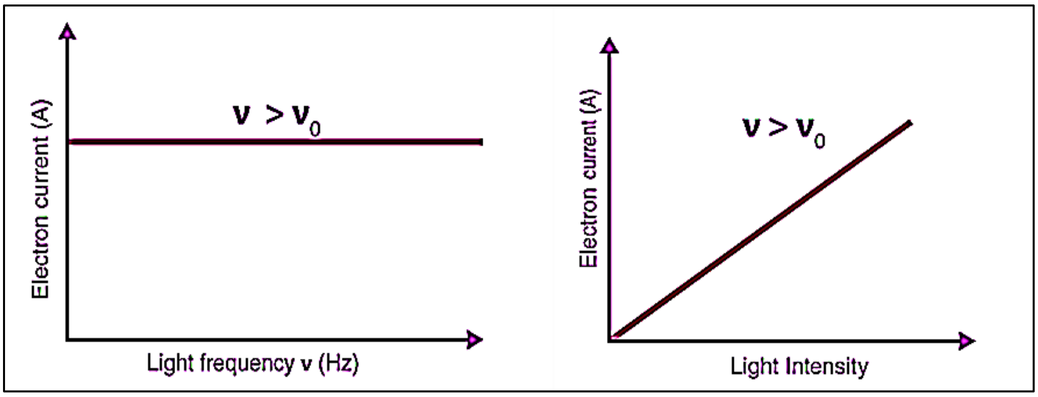
This section shows different graphs of the photoelectric equation as shown in Figures 6 to 8 (Singh & Chaturvedi, 2016):

- Photoelectric current versus Retarding potential for different intensities (Figure 6 (a)).
- Photoelectric current versus Retarding potential for different voltages (Figure 6 (b)).
- Electron current versus light frequency (Figure 7 (a)).
- Electron current versus light intensity (Figure 7 (b)).
- Stopping potential versus frequency (Figure 8 (a)).
- Electron kinetic energy versus light frequency (Figure 8 (b)).



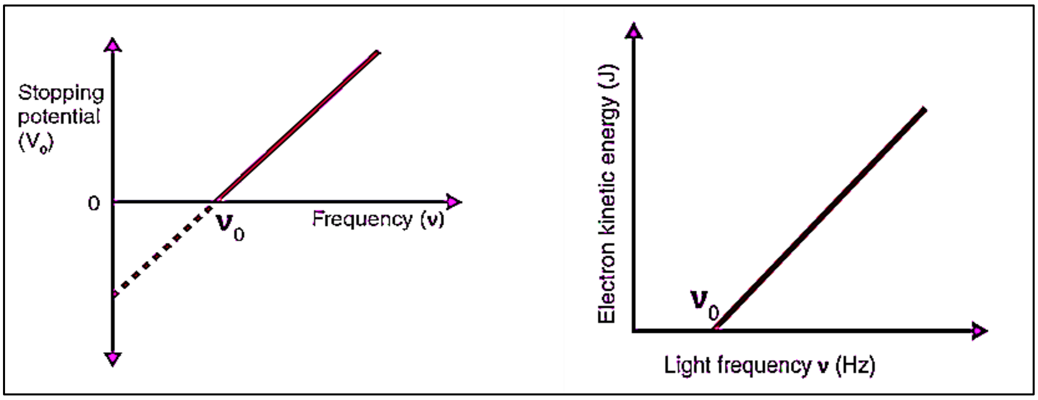
(a) (b)

Figure 6: Photoelectric Current Versus Potential for Different Intensities and Voltages



(a) (b)

Figure 7: Electron Current Versus Light Frequency and Light Intensity



(a) (b)

Figure 8: Stopping Potential Versus Frequency and Electron Kinetic Energy Versus Light Frequency

The generation of energy in solar panels represents the primary use of the photoelectric effect. The metal combinations in these panels enable the production of energy from a variety of wavelengths.

2. PV Cell-Module-Array Relationship

The development of photovoltaic power systems is contingent upon the presence of photovoltaic cells. The power output of a photovoltaic cell is typically restricted to a few watts due to surface area constraints, rendering it insufficient for the generation of higher wattages. As a result, a photovoltaic module is constructed by arranging photovoltaic cells in parallel or series. Photovoltaic arrays, which can be interconnected in series, parallel, or a combination of both, can generate the required current and voltage in a range of kilowatts to megawatts (Harjai, Bhardwaj, & Sandhibigraha, 2011).

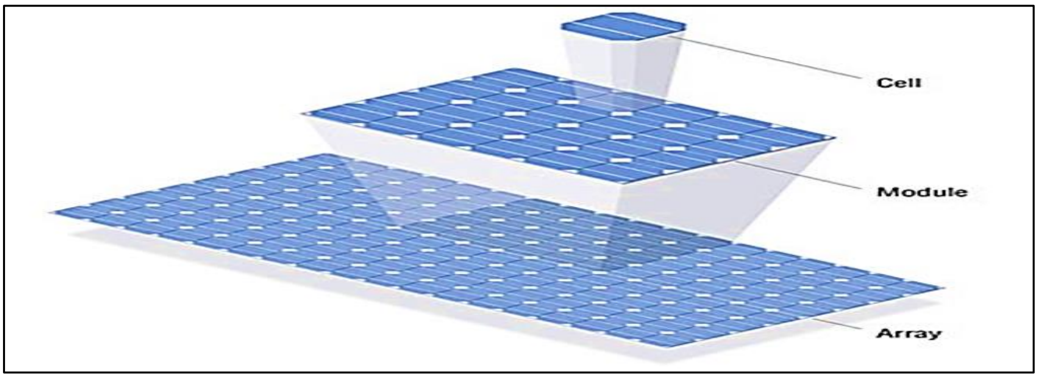


Figure 9: Relationship Among PV Cells, Modules, And Array
Source: Dwivedi, Bari, and Dwivedi (2013)

2.1. Photovoltaic Cell

Silicon remains the most ordinary material for PV cells; PV cells are p-n semiconductor junctions. In these cells, a thin layer of semiconductor is treated to produce a positive and negative electric field. The PV effect transforms solar radiation into electrical power when linked to a load. When sunlight interacts with the solar cell, the resulting electrical field generates a current flow. Photovoltaic (PV) cells are often connected in series to achieve high voltage and in parallel to attain high current, as each cell typically generates a low voltage of approximately 0.5 V (Ji et al., 2011).

2.2. Photovoltaic Module

Solar photovoltaic (PV) modules, which are made up of PV cells that are enclosed in a protective laminate, are capable of producing a significant quantity of electricity. Several cells make up a photovoltaic module, which is more generally known as a solar panel. One of the most significant benefits of photovoltaic modules is that they do not have any moving parts, which means that they do not contribute to noise or pollution. To create a photovoltaic module that has the output that is needed, photovoltaic cells are connected in either a series or parallel configuration. Consequently, photovoltaic (PV) array modules are typically connected in series to achieve the necessary voltage or in parallel to increase the system's current output (Miyatake, Veerachary, Toriumi, Fujii, & Ko, 2011). This is on account of the fact that the power output of a single module is insufficient to fulfill the energy requirements of a residential or commercial establishment.

2.3. Photovoltaic Array

Some modules make up the photovoltaic array. These modules are connected and contain photovoltaic cells that are arranged in either series or parallel configurations. For commercial purposes, a single photovoltaic panel is rarely sufficient. Within this manner, the photovoltaic array is composed of a number of different pieces. It is also possible to connect these units in series to raise the voltage or in parallel to raise the current from one rack to several racks. Both of these configurations are possible. The photovoltaic array is able to fulfill the requirement for power in this manner (Dwivedi et al., 2013).

3. Working Principle of PV Cell

Basically, the photoelectric effect is what makes a photovoltaic cell work. This effect turns electrical energy from the sun into electricity. When sunlight is received, and an electron is pushed out of the conduction band, this is called a photoelectric impact. A pair of electrons and holes are produced when sunlight is absorbed. Electrical power is then produced as a result of the device's structure dividing the electron and hole pair, with the positive terminal receiving holes and the negative terminal receiving electrons. Figure 3.10, which displays the key characteristics of the standard solar cells in use today, illustrates this process (King, Kratochvil, & Boyson, 2004). A variety of semiconductor materials are used to produce PV cells. For many years, silicon has been the sole material utilized in the production of solar cells. Silicon is still utilized in over 80% of processes despite the development of alternative materials and methods. Silicon is present everywhere and exists primarily as silicon dioxide. The three primary types of silicon solar cells are amorphous, polycrystalline, and monocrystalline. The two most commonly utilized varieties are monocrystalline and polycrystalline. The amorphous has a relatively poor efficiency and is used less frequently. Cadmium telluride (CdTe) or copper indium gallium (di) selenide (CIGS) have been used as materials for making modern solar cells (Zhou, Yang, & Fang, 2007).

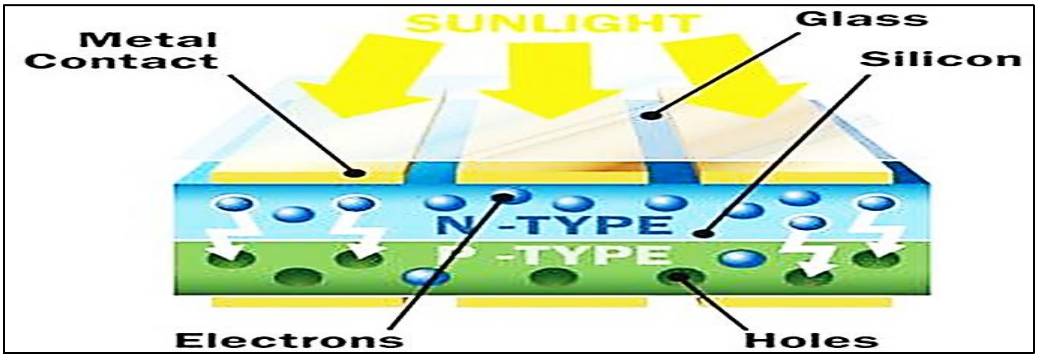


Figure 10: Working Principle of PV Cells
Source: Zhou et al. (2007)

4. Types of Solar Cells

The name of solar cells considers the materials used to create them, and such materials must exhibit specific solar radiation absorption capabilities. Some cells were designed in such a way that they were able to collect solar energy at ground level, while other types were created with the intention of being used in space. According to Bagher, Vahid, and Mohsen (2015), solar cells (SC) can be classified as either single-junction, which consists of a single layer of light-absorbing material, or multi-junction, which consists of multiple physical configurations. Russell Ohl is credited with the invention of the first solar cell based on silicon. The conversion of solar radiation (SR) into electrical power is accomplished through the utilization of thin silicon wafers, which were utilized in earlier photovoltaic solar cells. Electron holes are produced by each photovoltaic (PV) cell, which is composed of two distinct semiconductor layers (p-type and n-type). This is the fundamental idea behind current PV cells. In this configuration, an electron is released by absorbing energy from the photon that is striking it, and it then moves to a higher energy level when a sufficiently energetic photon strikes the junction between the p-type and the n-type. An electron and a hole are both produced simultaneously, which results in the generation of electrical power concurrently. The most common materials found in PV solar cells are "copper-indium-gallium-sulfide, copper-indium-gallium-selenide, cadmium-telluride, and silicon." These materials, which are discussed in the sections that follow, are used to categorize PV solar cells into several classes, as shown in the image below (Sharma, Jain, & Sharma, 2015).

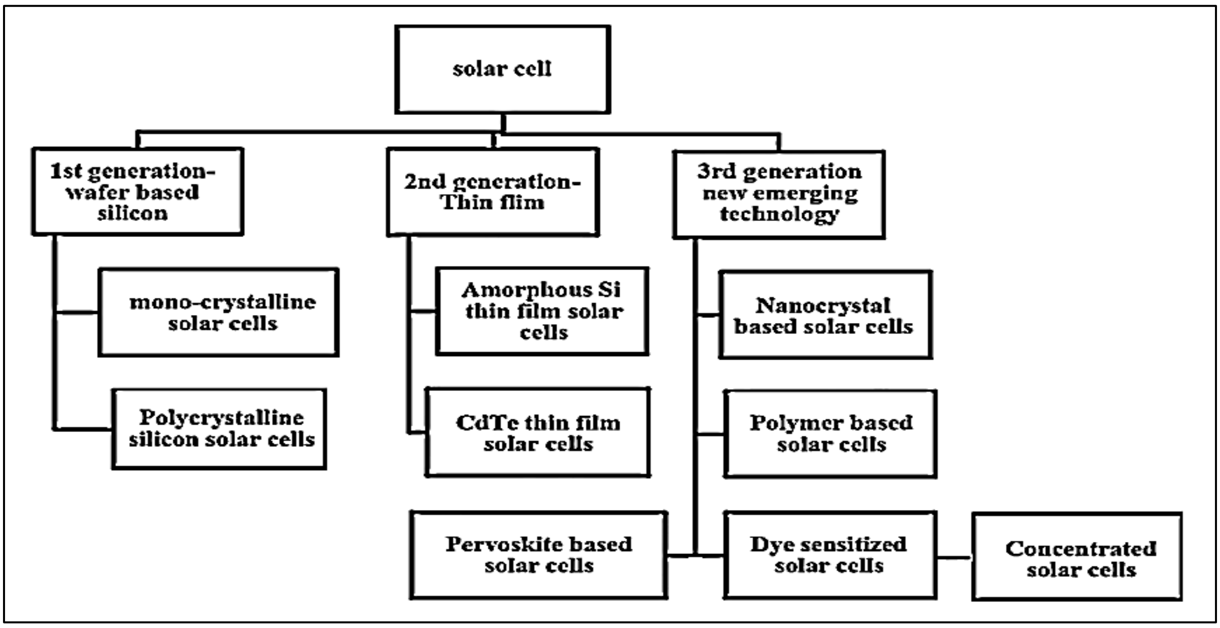


Figure 11: Different Solar Cell Technologies and The Current Development Trends

4.1. First Generation Solar Cell-Wafer Based

As previously mentioned, Si wafers are used to create the earliest solar cells (first-generation) due to their superior power efficiency, which makes them the most common technology. According to Sharma et al. (2015), there are two subgroups of silicon wafer-based technologies.

- Monocrystalline Si (MS) solar cells: As the name suggests, these cells are made from single silicon crystals using a method known as the Czochralski process. Cutting Si crystals from the enormous ingots during the making process is what it takes to do it. Because "recrystallizing" the cell is more expensive and takes more steps, precision engineering is used to make these huge single-crystal goods. It has been said that MS solar cells have an efficiency rate of 17% to 18%.

- Polycrystalline silicon (PS) solar cells: PS solar cells are created by joining numerous crystals; they are cheaper to create, accounting for about 48 % of the world's total solar cell production in 2008. During the creation, liquid Si is solidified into several crystal shapes. Despite being somewhat less costly to produce, their major drawback is that they are between 12% and 14% less efficient compared to MS solar panels (Sharma et al., 2015).

4.2. Thin Film Solar Cells (Second Generation Solar Cells)

These cells are called second-generation because they are less costly than earlier silicon wafer solar cells. While thin-film solar cells usually have photosensitive layers that are about 1 μm thick, silicon wafer cells can have photosensitive layers that are over 350 μm thick. The following types of thin-film solar cells (TFSC) are distinguished:

- Amorphous silicon (a-Si) thin-film solar cells (TFSC) were the first solar cells produced on an industrial scale. They utilize various low-cost polymers and substrates, as a-Si solar cells can be fabricated at low processing temperatures. A-Si solar cells require less processing power, resulting in greater availability and lower costs. In the context of solar cells, "amorphous" refers to silicon that is characterized by a lack of high organization, non-crystallinity, or an absence of a distinct atomic arrangement within the lattice structure. The doped Si material is applied to the substrates' back to create these cells; hence, such cells usually have a silverish conducting side and a dark brown reflecting side. However, the problem with a-Si cells is their low and almost unpredictable efficiency. The cell efficiency as a model is significantly low (4% to 8%), and they work well at high temperatures and are appropriate for shifting weather patterns with brief periods of sunshine (Sharma et al., 2015).

- Cadmium Telluride (CdTe) TFSC: Among TFSC, CdTe is the leading contender for reasonably priced PV devices. CdTe has a band gap of roughly 1.5 eV, good chemical stability, and excellent optical absorption coefficient. These features made CdTe the most sought-after material for TFSC creation. Light absorption is facilitated and improved by the excellent crystalline compound semiconductor CdTe, which has a straight band gap. Cadmium sulfide layers are often interposed to create a p-n junction diode. The manufacturing process begins with the selection of substrate glass, which is composed of polycrystalline elements. Then, in the deposition step, several CdTe solar cell layers are applied to a substrate utilizing several cost-effective techniques. CdTe exhibits a direct optical band gap and, as previously determined, a high absorption coefficient. Its efficiency, therefore, usually falls between 9 and 11 percent. Polymer substrates can be used to create flexible CdTe solar cells; however, some environmental issues have restricted their usage. Cadmium, a heavy metal capable of bioaccumulation in humans, animals, and plants, is regarded as posing potential health hazards. Cd-based hazardous material disposal and recycling can be costly and harmful to the environment. Hence, the significant problems with this CdTe technology are the health risks associated with its use and the restricted availability of Cd (Sharma et al., 2015).

- CIGS Solar Cells: These cells are quaternary semiconductors consisting of four elements: copper, indium, gallium, and selenium. They exhibit a straight band gap. CIGS exhibits an efficiency of approximately 10 to 12 percent greater than that of CdTe TFSC. These thin film technologies exhibit high efficiency and cost-effectiveness, making them particularly promising. The following methods are used to process CIGS: printing, evaporation, sputtering, electron beam deposition, and electrochemical coating. Furthermore, sputtering can be done in a single step or two and it involves deposition and subsequently interaction with selenium. Evaporation and sputtering are comparable, though, in that they can be applied to one, two, or more processing steps. Glass plates, polymer substrates, steel, aluminum, and other materials can be used as substrates for CIGS material. One of the advantages of CIGS thin film solar cells is their extended lifespan without significant deterioration. These CIGS features point to a simple way to increase efficiency (Sharma et al., 2015).

4.3. Third Generation Solar Cells

Despite being a promising new technology, third-generation (3G) cells have not yet undergone extensive commercial research. Sharma et al. (2015) state that the vast majority of 3G solar cell types that have been created include:

- Solar cells are based on nanocrystals, which are also popularly known as quantum dot (QD) solar cells. Semiconductors are materials with nanocrystal dimensions that are utilized in the manufacturing of solar cells. Semiconductors mainly come from transition metal groupings. Materials commonly utilized in quantum dots (QD), including porous silicon or porous titanium dioxide, typically exhibit crystal sizes within a few nanometers and are collectively designated as QD. With the advancement of nanotechnology, these nanocrystals are intended to supplant more extensive materials such as Si, CdTe, or CIGS. Through a theoretical formulation of the quantum dot-based solar cell concept, the p-i-n solar cell was produced. This was accomplished by utilizing the self-organized As/GaAs system. Before being deposited on the silicon substrate, nanocrystals are typically pre-mixed in a bath before the process begins. Within a compound semiconductor solar cell that is considered to be standard, an electron is excited by a photon, which ultimately results in the creation of one electron-hole pair. Light causes the production of many electron-hole pairs in a quantum dot that is formed of a substance that is comparable to the material being exposed to light.

- Polymer solar cells are characterized by their flexibility as a result of their polymer composition. Tang et al. were the first to develop polymer sun cells at Kodak Research Lab. A polymer-structured composite (PSC) is made up of tiny functional layers that are placed on a polymer foil or ribbon and are joined consecutively. It is often made up of a polymer, which acts as a donor, and fullerene, which acts as an acceptor. It has been established that conjugated and conducting polymers, in addition to other organic molecules, are materials that are capable of absorbing sunlight. The photovoltaic effect is a technique that transfers energy from electromagnetic radiation into electrical current. This effect is the basis for the operation of the photovoltaic solar cell (PSC). With the implementation of this method, a new era in the use of polymer materials for solar power collection has begun. After conducting significant parameter tuning, the researchers were able to achieve an efficiency that was greater than 3.0% for PSCs of the PPV type. The creation of flexible solar devices, which include textiles and fabrics, has been made possible by the distinctive properties of photovoltaic solar cells (PSCs).

- Dye-Sensitized Solar Cells (DSSC): Recent research has focused on molecular modification to boost solar efficiency and light energy capturing using nanotechnology. The earliest DSSC was developed in Switzerland by Michel Gratzel. These cells often utilize dye molecules between the different electrodes and are mainly composed of four components - a counter electrode, a semiconductor electrode, a dye sensitizer, and a redox mediator. The simple conventional processing methods, such as printing procedures, make DSSCs appealing; they are also inexpensive, transparent, and incredibly adaptable. The distinctive feature of DSSC is nano-grained TiO2 coatings photosensitization in conjunction with visible optically active dyes, which increases the cells' efficiency above 10%. However, there are several challenges, like stability issues and dye molecule degradation. The reason for this is that sensitizers' low optical absorption reduces conversion efficiency. The lifespan and stability of the cells are reduced as a result of the dye molecules' typical degradation during exposure to UV and infrared light. Furthermore, applying a barrier layer could make production more costly and less effective.

- Concentrated Solar Cells: These cells have been around since the 1970s but have recently advanced to collect solar energy from different angles and focus on a small region above the PV cells. The use of numerous mirrors and lens arrangements in such cells drives this feat. A significant amount of thermal energy is produced as a result of the convergence of solar radiation. This thermal energy is then employed by a heat engine that is handled by a power generator that has integrated controls of its own. Concentrated photovoltaics, often known as CPVs, showcase a significant amount of potential in the solar sector. The power of the lens systems allows for the classification of these cells into three different categories: low, medium, and high-concentration solar cells. Numerous advantages are associated with the utilization of concentrated photovoltaic technology. These advantages include solar cell efficiencies that exceed forty percent, the absence of moving parts and thermal mass, rapid response times, and the flexibility to scale to a variety of dimensions (Sharma et al., 2015).

4.4. Perovskite-Based Solar Cells

Perovskites, which are represented by the symbol ABX3 (where X is a halogen (I^-, Br^-, or Cl^-) and A and B are cations of different sizes), are a relatively new development in the field of solar cell technology. Perovskites offer numerous advantages over silicon and thin-film solar cells. Perovskite-based solar cells require less sophistication and have an efficiency of up to 31%, in contrast to traditional silicon-based solar cells, which require expensive, multi-step processing at high temperatures while also being expensive. It is intriguing to note that Volkswagen, in a recent piece of work, stated that these perovskites might also play a significant part in the batteries that would be used in next-generation electric vehicles. Perovskite solar cells, on the other hand, are experiencing problems with their endurance and stability at the moment. The substance deteriorates with time, which lowers overall efficiency. Therefore, there is a need for more research before these cells can be commercialized. Next-generation solar cells may become exponentially more helpful due to a recently identified nanotube structure that can carry higher electrical charges than previously described.

Currently, the majority of solar cells utilize silicon for light absorption; however, due to silicon's inefficiency, researchers have engineered carbon nanotubes to enhance the light-absorbing efficacy of the cells. Still, because they are challenging to arrange, the nanotubes have, up until now, been haphazardly positioned within the solar cells in less-than-ideal configurations. According to a study from Exeter University in Britain, a new type of perovskite solar panels could make it possible to turn solar energy into electricity for homes at a lower cost than previously possible (Bagher et al., 2015). These kinds of materials will be considered the Holy Grail in those nations since they can simultaneously generate electricity and shade windows. Perovskite solar panels, with a thickness of nanometers, are projected to be over 40% less expensive and 50% more efficient than currently commercially produced panels. Perovskite solar panels, unlike other types, can absorb a significant portion of the solar spectrum and operate effectively under diverse atmospheric conditions as well as direct sunlight.

Sundaram stated that this type of material for solar cells performs significantly better in diffused conditions than other types of solar cells. "While it may not achieve complete accuracy, it will represent a significant improvement over the current state." Scholars from many parts of the globe (Americas, Europe, Asia, etc) have already studied the material. The Exeter study claims that the vacuum-based processing processes used in existing commercial solar power generating products, such as silicon or thin film-based technologies, make them expensive. Perovskite panels have a reasonably simple production method, but before companies start producing them on an industrial scale, researchers must test the material in various settings to better understand its characteristics, the report stated. The IEA has earmarked solar energy as the potential largest energy source by 2050, and its market has been increasing due to current efforts by different governments towards CO_2 emission regulations (Bagher et al., 2015).

5. Characteristics of PV Cell

A single photodiode performs the function of a solar cell. It is possible to accurately represent the single-cell equivalent circuit by utilizing a current source that is dependent on both temperature and irradiation in conjunction with an inverted diode that conducts reverse saturation current. In order to account for the inherent shortcomings of solar cells, the model incorporates both shunt and series resistances, as shown in Figure (12). The intrinsic series resistance (Rs) is reduced to a negligible value when there are obstructions in the electron flow channel that extend from the n junction to the p junction. The leakage current demonstrates a markedly elevated value, leading to shunt resistance (Rsh) (Pandey et al., 2016).

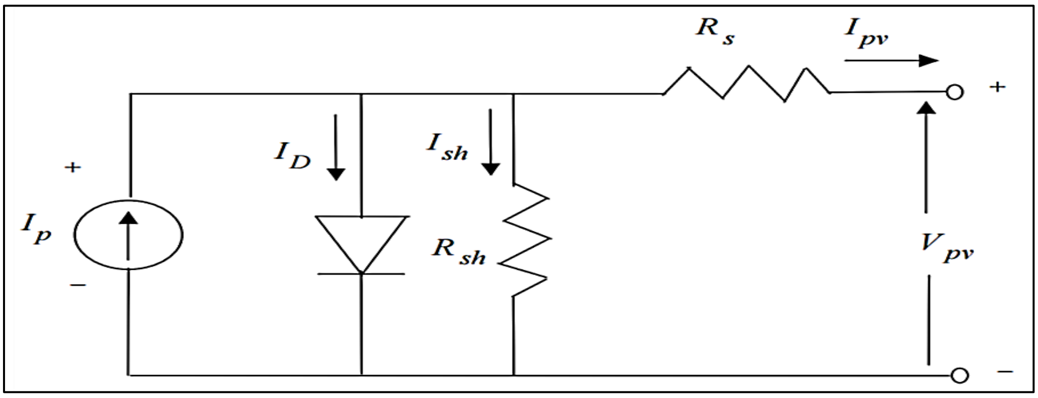


Figure 12: The Circuit Model of a Solar Cell

You can see the solar cells' electrical equivalent circuit in Figure (12). Using this analogous circuit, we can derive the following simplified current equation:

$$I_{pV} = I_p - I_D - I_{SH} \quad (8)$$

Where:

IPV = the generated photocurrent in the cell
ID = the current passing through the diode (D)

The diode equation can be used to replace the ID as follows:

$$\mathrm{I_D} = \mathrm{I_O}\mathrm{I_O}\left[e^{\left(\frac{q(V_{PV}+R_S I_{PV})}{NKT}\right)} - 1\right] \quad (9)$$

Hence, the current generated from solar cells can be expressed as:

$$\mathrm{I_{PV}} = \mathrm{I_P} - \mathrm{I_O}\left[e^{\left(\frac{q(V_{PV}+R_S I_{PV})}{NKT}\right)} - 1\right] - \frac{V_{PV} + R_S I_{PV}}{R_{SH}} \quad (10)$$

Where:

Ipv = PV current,
IO = initial current,
RS = solar cell’s series resistance,
RSH = solar cell’s shunt resistance,
q = electric charge 1.602×10^(-19) C,
N = ideality factor of diode,
k = Boltzmann constant (1.38 × 10-23 J/K),
T = temperature (K).

The equation above explains the ideal solar cell-generated current devoid of parasitic effects. Specific amounts of current often leak from an actual solar cell through shunt resistance Rsh.

The PV array's features significantly influence energy generation, and each model has variations in these features. The open circuit voltage (VOC), short circuit current (ISC), and maximum power point (VMPP, IMPP) constitute the three essential elements of a photovoltaic characteristic, as illustrated in Figures 13 and 14 (Sethy, 2013).

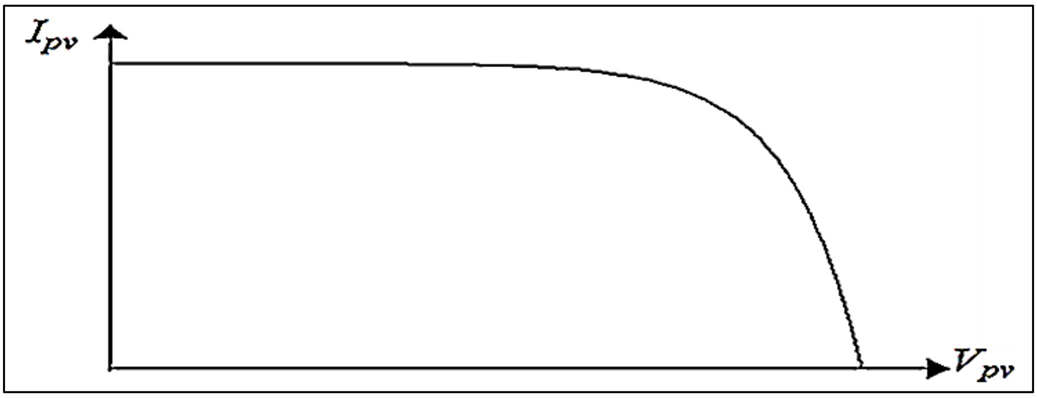


Figure 13: Characteristic of PV Cell

The IPV-VPV operating characteristic of a solar cell is shown in Figure (14), which is up there. Several individual PV cells are connected to create the PV array, which in turn achieves the desired power rating. Multiply the current by the total number of cells linked in parallel and the voltage by the total number of cells connected serially to find the features of PV arrays (Takun, Kaitwanidvilai, & Jettanasen, 2011).

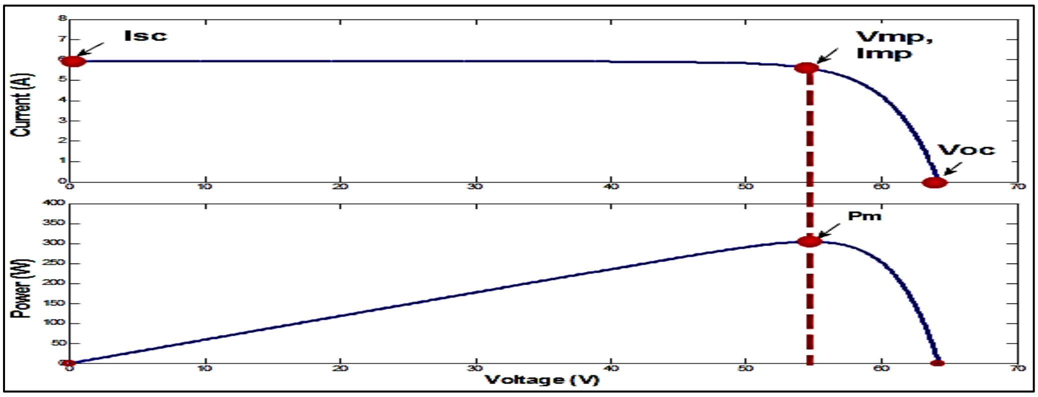


Figure 14: PV Cell Has Three Important Operating Points

5.1. Open Circuit Voltage

The open circuit voltage (VOC) is measured when there is no current flowing through the cell. More specifically, at the point where the current through the cell is equal to zero, the voltage is equal to the VOC. The VOC represents the most considerable voltage difference that occurs across the cell during a forward-bias sweep (FBS) in the power quadrant. In the context of the forward-bias power quadrant, the following can be said:

$$VOC = VMAX \quad (11)$$

Figure 12 illustrates the open circuit voltage at Point A, while Figure 15 depicts the open circuit voltage excluding the shunt current.

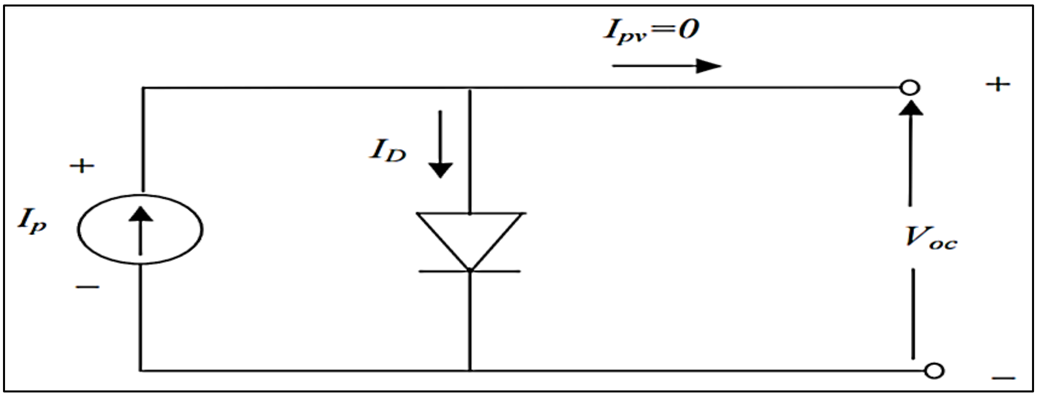


Figure 15: Open Circuit Voltage

$$I_P - I_O\left[\frac{qV_{OC}}{e^{nKT}-1}\right] = 0 \tag{12}$$

$$V_{OC} = \frac{nKT}{q}\ln\left[\frac{I_P + I_O}{I_O}\right] \tag{13}$$

5.2. Short Circuit Current

When the voltage equals zero, a short circuit current (ISC) is said to have occurred.

At $V = 0, I = ISC$ (14)

ISC is defined as the ideal current value in the power quadrant and is experienced during the early phase of the FBS. It is expressed as ISC = IMAX = Iℓ for the forward-bias power quadrant. ISC is encountered during the early phase of the FBS. In Figure (16), Point B depicts ISC. Figure 14 presents ISC where the series resistance RS is neglected.

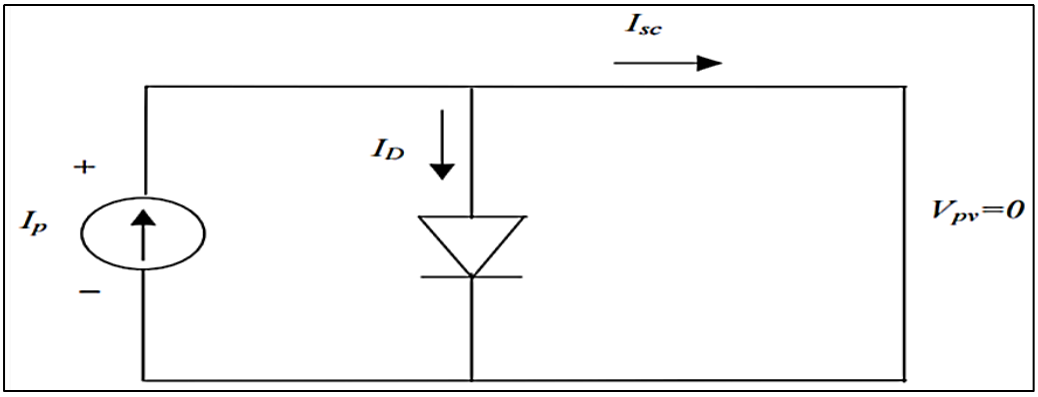


Figure 16: Short Circuit Current

$I_{SH} = I_P$ (15)

The selection of parasitic components for the model significantly impacts performance in PV modules. The behavior of PV modules can be modeled to understand the shunt and series resistance properly, as per (Sriram & Shahidehpour, 2005). In Figures 17 and 18, the impact of altering the shunt and series resistance of PV models on the I-V characterization is presented.

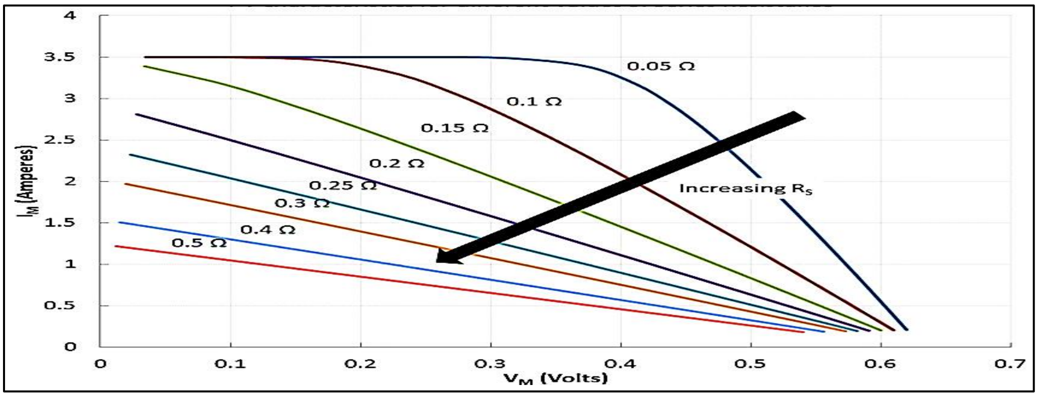


Figure 17: Different Series Resistance And I-V Characteristics at Fixed Illumination
Source: Ji et al. (2011)

The amount of light of the cells has been tuned, and a parametric study was carried out with series resistance RS ranging from 0.05 Ω to 0.5 Ω. Because there is no current flowing through a short circuit with an open-circuit voltage of zero, the series resistance appears to have a negligible impact. The conditions that are related to short-circuiting are the key factors that affect remote sensing. Within the framework of the solar cell concept, the diode is positioned in parallel with both the series resistance and the load resistance. According to Bowden and Rohatgi (2001), when the value of RS is increased, the voltage that is across it also increases, which in turn causes the voltage that is across the diode to grow proportionally. As the voltage increases, the flow of photonic current through the diode increases, which subsequently leads to a drop in the output current. Both the load and the light conditions, as well as the proportion of shade that the cells get, affect the fluctuation that occurs through the diode receiver. Specifically, Ji et al. (2011) highlight the fact that series resistance is a substantial concern at high current densities, mainly when conditions are characterized by bright lighting.

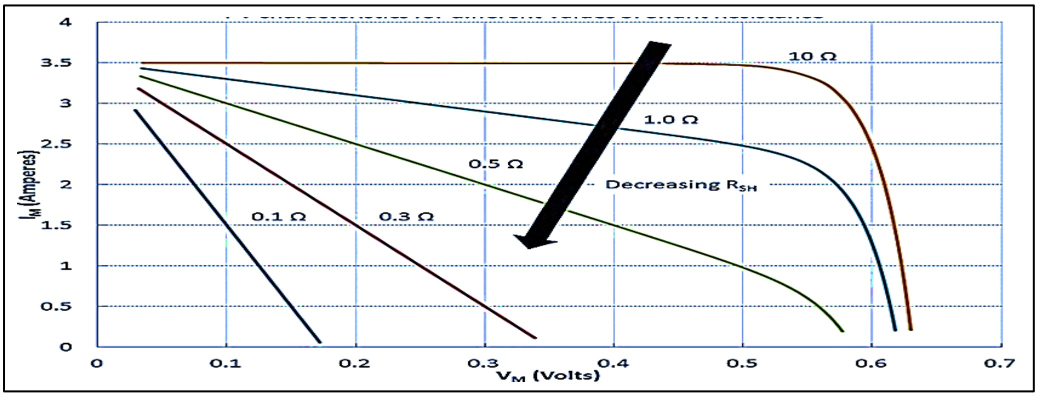


Figure 18: I-V Characteristics with Varying Shunt Resistance at Fixed Illumination
Source: Singh (2011)

When conducting a parametric analysis, it was observed that the RSH values were adjusted between 0.1 Ω and 10 é. Additionally, it was observed that the light intensity remained steady throughout the SC. As can be seen in Figure 16, the effects of RSH are demonstrated to be more pronounced in open-circuit settings than in short-circuit conditions. A comparable relationship exists between the RSH and the combination of the load resistance and the series resistance. As a consequence of the reduction in RSH, the overall output resistance is reduced as well. This eventually leads to a reduction in the voltage that is present across the solar cell, which in turn causes the parallel diode that is contained within the cell to become smaller. Between the load and the output voltage, there is a reduction in the voltage. According to Singh (2011), the I-V outlines become less distinct as the shunt resistance RSH undergoes a drop.

6. Specifications of the Solar Cell Used in the Study

Table 1 presents the features of the solar cells and photovoltaic modules applied in this work. One Soltech 1STH-230-P solar panel is used in solar photovoltaic modules.

Table 1
The characteristics of the Solar Cell and PV modules

Parameter	Value
Electrical characteristics of the PV module	
Parameter	**Value**
STC Power Rating P_{mp}	230 W
PTC Power Rating P_{mpp}	203.1 W
PTC/STC Power Ratio	88.3%
Open Circuit Voltage V_{oc}	37.1 V
Short Circuit Current I_{sc}	8.18 A
Voltage at Maximum Power V_{mp}	29.9 V
Current at Maximum Power I_{mp}	7.65 A
Panel Efficiency	14.7%
Fill Factor	75.8%
Power Tolerance	-3.00% ~ 3.00%
Maximum System Voltage V_{max}	600 V
Maximum Series Fuse Rating	15 A
Temperature coefficients of the PV module	
Parameter	**Value**
Temperature Coefficiency of I_{sc}	0.010 %/ºC
Temperature Coefficiency of V_{oc}	-0.36 %/ºC
Temperature Coefficiency of P_{mp}	-0.50 %/ºC
Mechanical characteristics of the PV module	
Parameter	**Value**
Cell Type	Polycrystalline Cell
Cell Size	156 ×156 mm
Cells	6 × 10
Dimensions	1626.0 × 964.0 × 46.0 mm (38.0 × 64.0 × 1.8 inch)
Weight	20.0 Kg (44.1 lbs)
Operation conditions of the PV module	
Parameter	**Value**
Nominal Operating Cell Temperature (NOCT)	47.4ºC
Operating Temperature	-40.0ºC to 85.0ºC

7. Types of Photovoltaic Systems

There are three main types of solar photovoltaic and storage systems: those that are directly connected to the grid, those that operate independently of the grid, and those that combine the best of both worlds, utilizing energy storage (Awasthi et al., 2020).

7.1. Grid-Tied or Grid-Direct PV System

This solar system is essential and uses a standard grid-connected inverter. Energy storage is not possible in a grid-tied solar PV system since there is no battery bank for energy storage; hence, it is valid only during sunny days. Hence, it is a cost-efficient system that can be quickly built and maintained. The mechanism is schematically illustrated in Figure (19). Energy cost reduction remains the major aim of building grid-tied systems, and being that the solar panels typically supply more electricity than needed during peak production, the excess energy is channeled to the system rather than being stored in batteries. The levelized cost of energy (LCOE) of the system may be further decreased by selling surplus electricity generated by the solar panel, thereby generating additional revenue. The direct current produced by photovoltaic panels requires conversion to alternating current via an inverter. A limitation of the grid-direct approach is its availability solely during daylight hours. For instance, there is no backup power to use during blackouts as the system has no battery to save excess energy. Although this drawback can be addressed by storing the power produced throughout the day in a battery bank, this new configuration will ultimately raise the system's cost (Awasthi et al., 2020).

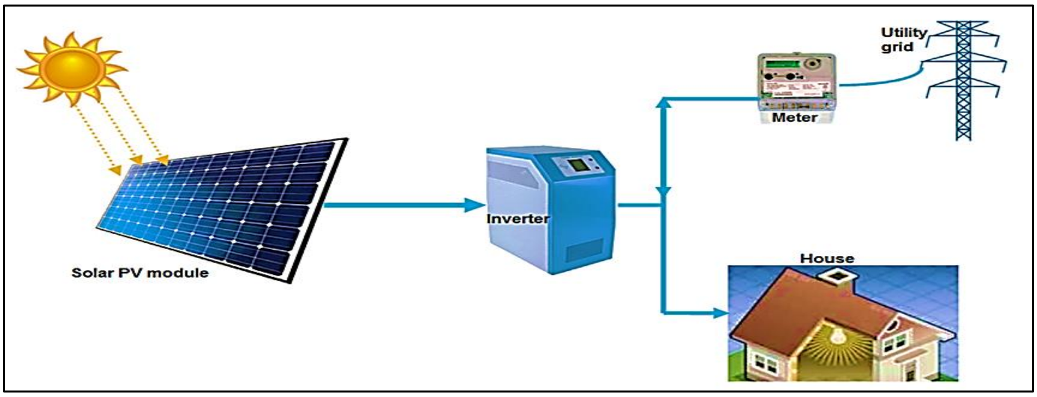


Figure 19: Grid Tied/Direct PV System

7.2. Standalone/off Grid Solar PV System

This is a beneficial alternative for consumers whom the public grid cannot accommodate. These systems utilize batteries to store electricity generated during the day for consumption at night. When designing such systems, numerous factors are taken into account, especially annual weather variations. During extended periods of darkness or snowfall, such systems frequently utilize backup generators powered by diesel or petrol. The AC output of backup generators can be converted into DC for immediate use or battery storage. This system's advantage is in its capacity to provide sufficient electricity for a residence and to energize locations distant from the grid, as seen schematically in Figure (20). Awasthi et al. (2020) assert that off-grid systems are costlier and possess more components than grid-connected systems.

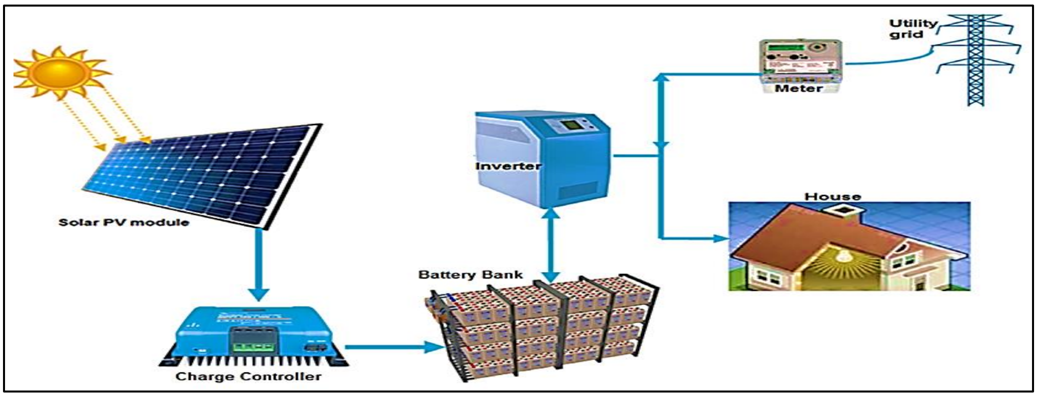


Figure 20: Standalone/off grid PV system

7.3. Grid/hybrid or Grid Interactive System

This setup will be suitable for customers who want a battery backup and are already linked to the public grid, as it boasts the positives of both grid-linked and off-grid systems. The many incentives offered by this approach can help lower utility costs; additionally, the batteries' stored energy can be used during periods of high demand (Awasthi et al., 2020).

8. Photovoltaic Applications

Passive and active solar technologies are developed based on how such systems capture, convert and distribute sun energy. PV systems have been used for a variety of purposes. Radios, fans, lamps, watches, calculators, and outdoor lighting all run on solar energy. Standalone systems consume power as generated and, as such, are a helpful application of PV systems Mishra (2012); examples of such applications include:

- Lighting: PV systems are the perfect source of lighting for remote locations such as parking lots, information signs, streetlights, and homes because of the availability of low-power DC.
- In communications systems, PV systems can be applied to power transmitters, portable computers, cellular phones, satellites, mobile radio systems, etc.
- Photovoltaic systems can provide power to informational signs that are not connectable to the electrical grid, such as traffic warning sirens, airplane beacons, railroad signage, and navigational beacons.
- PV systems can also be used to pump water directly for irrigation, rural usage, and livestock farming.
- Vehicles: Automobile batteries can be charged using solar power.

The solar power industry has experienced a significant increase in installed capacity worldwide and a sharp decline in installation prices over the past ten years. Over the previous ten years, installed capacity has reached > 600 GW from 40 GW, as per the International Renewable Energy Agency (IRENA), and the associated cost of PV modules has dropped by 80%. In 2020, over 140 GW of new solar installations were documented globally, and this trend has persisted. With solar energy being a free resource, PV technology offers countries the opportunity to modernize their energy infrastructure and hasten the de-carbonation campaign. However, is a country's or region's PV power potential sufficient to utilize solar electricity, and if so, on what scale? This paper aims to provide additional insight into this subject, which is frequently posed by both businesses and policymakers. The Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund of the World Bank, commissioned and financed the development of the web-based Global Solar Atlas. Solargis has recently calculated global data that illustrates the solar resource and photovoltaic power output for each country worldwide. The data sets were subsequently provided in a standardized, high-resolution format. This data enables high-level comparisons of theoretical, practical, and economic solar potential among nations and regions (World, 2020).

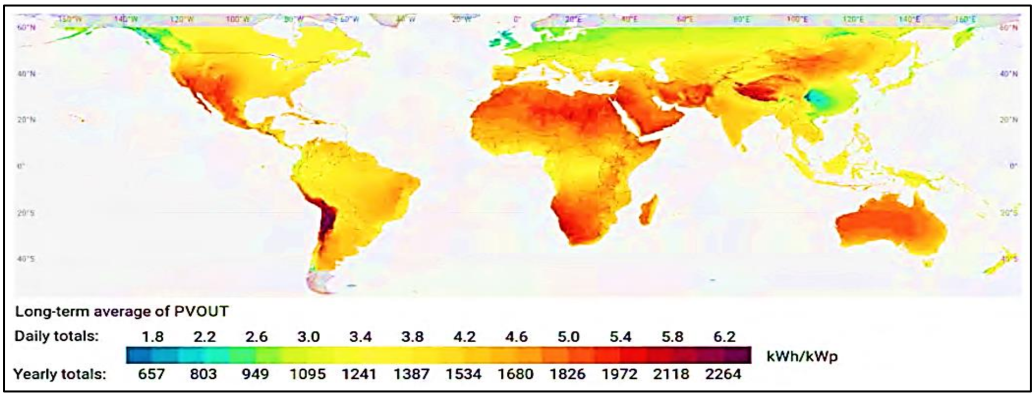


Figure 21: Feasible Solar PV Energy Potential: Long-Term Yearly Average Of Daily/Yearly Summaries

The payback period, return on investment for the owner or operator, and levelized cost of energy (LCOE) are approaches employed to assess economic viability. This study concentrated on the notion of LCOE as it facilitates the comparison of various power-generating systems, encompassing a broad range of renewables and fossil fuels. Although each technology may require somewhat different inputs to meet its own needs, LCOE is generally calculated by dividing the total lifetime expenses of building and operating a power plant by the amount of electricity generated over that lifespan; the following formula can be used to interpret it (World, 2020):

$$LCOE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \quad (16)$$

Where:

LCOE = Levelized cost of energy (electricity)
N = Period of analysis (yrs)
Cn = Annual project costs for year n ($), including operational expenditure (OPEX), capital expenditure (CAPEX), taxes, loan financing, and incentives (if applicable)
Qn = Yearly generated electricity for year n by the system (kWh)
d = Discount rate (real or nominal)

Consequently, even in regions with minimal or absent solar power installations currently, the PVOUT metric may assess the potential solar power generation across different countries. The Global Solar Atlas characterizes PVOUT as the long-term power output per unit of installed photovoltaic capacity, quantified in kilowatt-hours per installed kilowatt-peak (kWh/kWp). Evaluation based on potential output reveals that many countries that are not recognized as major solar power producers rank highly, while several nations with substantial solar installations demonstrate significantly lower suitability for solar production. The World Bank reports that Namibia has the highest photovoltaic output potential globally, with a national average PVOUT measurement of 5.38 kWh/kWp/day (Maguire, 2023).

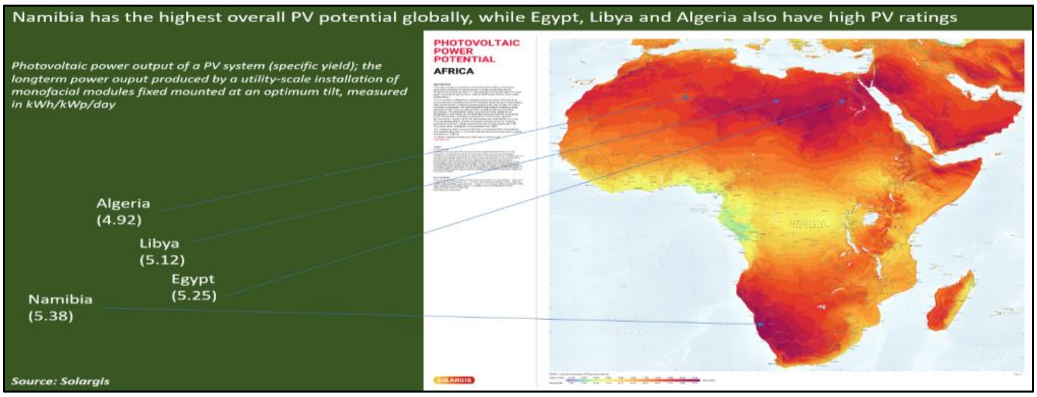


Figure 22: Africa's Solar PV Power Potential

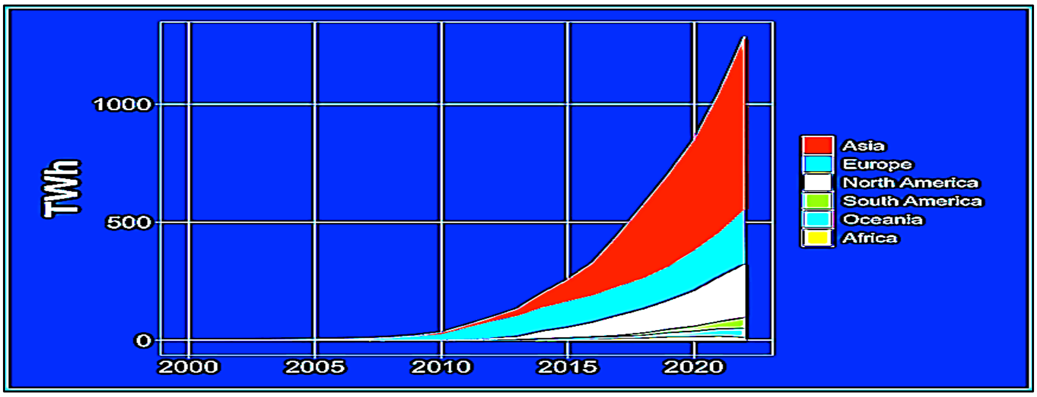


Figure 23: World Solar PV Generation Yearly
Source: Wikipedia (2022)

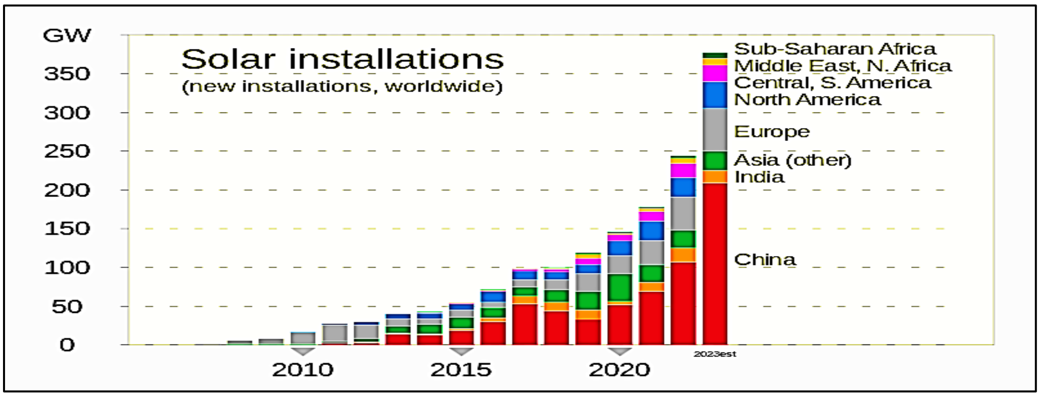


Figure 24: New Solar Installations - Annually by Region Or Country
Source: Wikipedia (2022)

9. Solar PV Array under Partial Shading Condition

The phenomena of unequal irradiation exposure over a PV string due to coverage from shadows of nearby images, such as pole and building shadows, is referred to as partial shading. Figure (25) depicts a schematic of a photovoltaic string with four modules, partial shading, and uniform irradiation (Ram & Rajasekar, 2017). Non-uniform irradiation causes hot spots to appear in panels that get less radiation, which lowers the PV array's output power. Therefore, to protect the panel from hotspots, a bypass diode is placed in parallel; this configuration prevents heat stress on PV modules and helps prevent damage to PV panels.

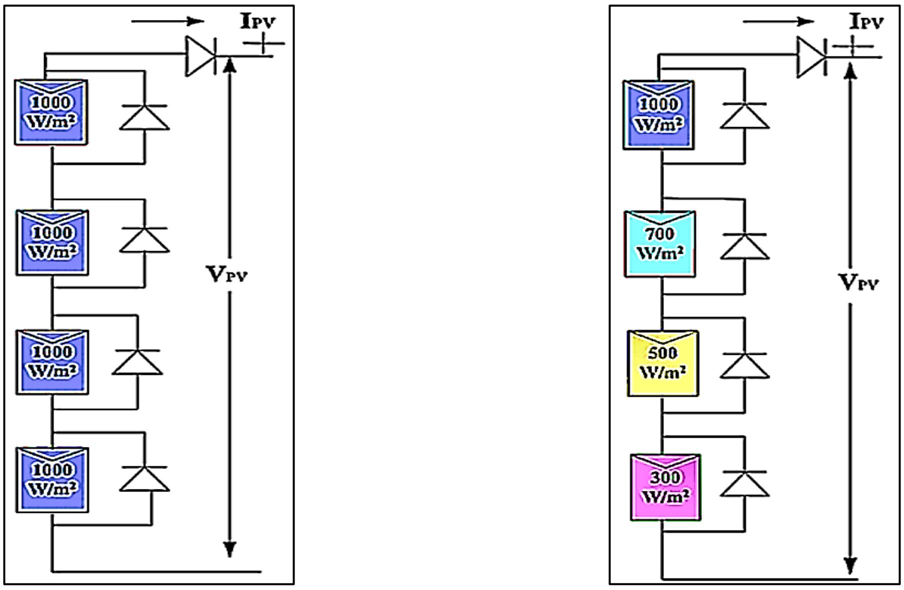


Figure 25: PV patterns for (a) Uniform irradiation and (b) Partial shaded condition
Source: Ram & Rajasekar (2017)

Partial shading results in distinct steps in the I-V curve and the emergence of multiple peaks in the P-V curve (see Figure 26). Thus, monitoring the global maximum power point under these conditions requires the implementation of technologies such as MPPT controllers. These controllers should be designed to accommodate various dynamic irradiation scenarios to ensure the attainment of the global maximum (Ram & Rajasekar, 2017).

It is commonly known that a solar array's output power capacity will decrease if it is partially shaded. As the reduction in energy production frequently does not correspond directly to the shaded area, it cannot be ascertained directly. According to some earlier research, the shaded area and a drop in sun irradiation are directly correlated with a decrease in electricity generation. This idea only applies to a single cell. Căluianu, Notton, Colda, Caluianu, and Damian (2009) indicate that the array-level power reduction exhibits a significant deviation from linearity in the shaded section.

A variety of factors can influence a PV system's performance. Shading is one of the most important factors; a shadow cast on the exterior of the PV modules is known as shading, and it will reduce the system's energy output; it affects the power, voltage, and current (the three essential PV module characteristics) (Pachpande & Zope, 2012). The array output fluctuates significantly throughout the day due to shifting irradiation, and this array output fluctuation is to be expected. It is challenging to attain consistent lighting concentration in a panel, though, because of unforeseen shading effects caused by many environmental factors like dust and clouds (see Figure 27). The influence of shading is contingent upon the module type, fill factor, bypass diode placement, shading intensity, and string configuration. Energy loss can result from shading and voltage mismatches between parallel threads and current mismatches within a PV string (Alsayid, Alsadi, Jallad, & Dradi, 2013; Bhadoria & Narvey, 2014).

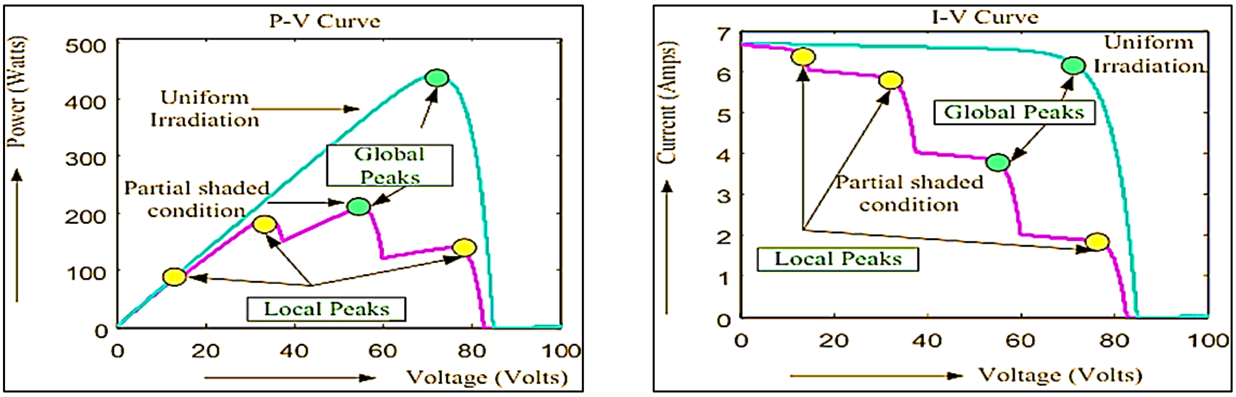


Figure 26: I-V And P-V Curve for Uniform and Partial Shaded Condition
Source: Ram and Rajasekar (2017)

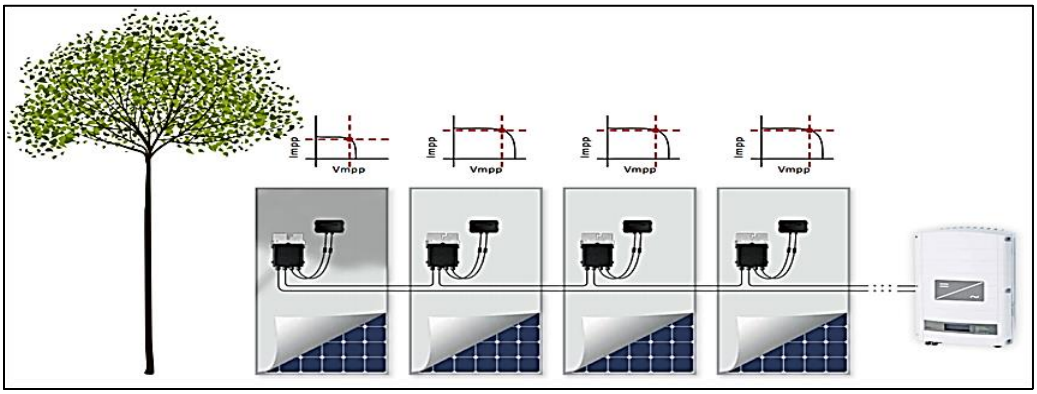


Figure 27: Partial Shaded Module
Source: Alsayid et al. (2013)

Shading has a significant impact on PV solar panels; it is nearly impossible to completely prevent shading in PV systems (Ramaprabha & Mathur, 2009). Partial shading often alters the overall I-V and P-V curves of photovoltaic modules during the analysis of their electrical properties. In non-uniform irradiation scenarios, the I-V and P-V characteristics of solar panels demonstrate increased complexity owing to the existence of multiple maximum power points (MPPs). Figures 28 and 29 illustrate how this impact might change significantly in shape from a typical unshaded curve.

A shadow cast on a photovoltaic module will lower its overall output power through two mechanisms: decreasing energy input and improving energy losses. The PV module will experience a power loss of about 30% even though only one cell is shaded. The more shaded cells there are, the higher the power losses will be. The discrepancy between the I-

V curves of the various modules serves as an example of how the partial shading issue deforms the overall I-V curve (Suman et al., 2012).

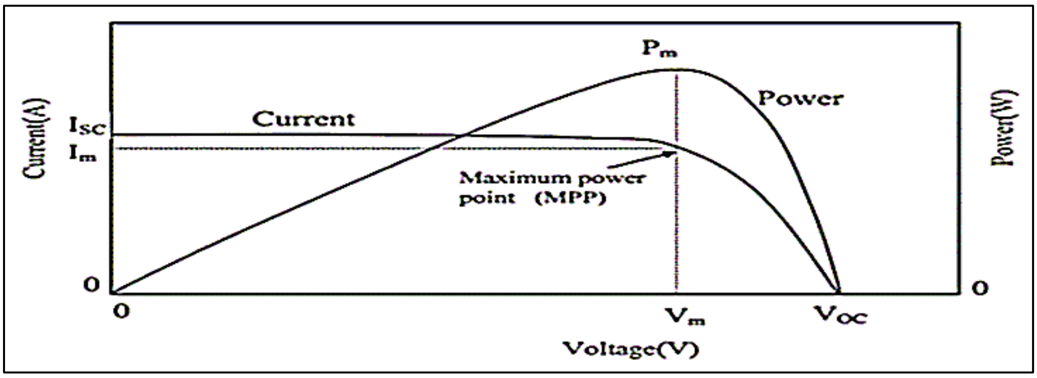


Figure 28: I-V And P-V Characteristics of The Solar Array

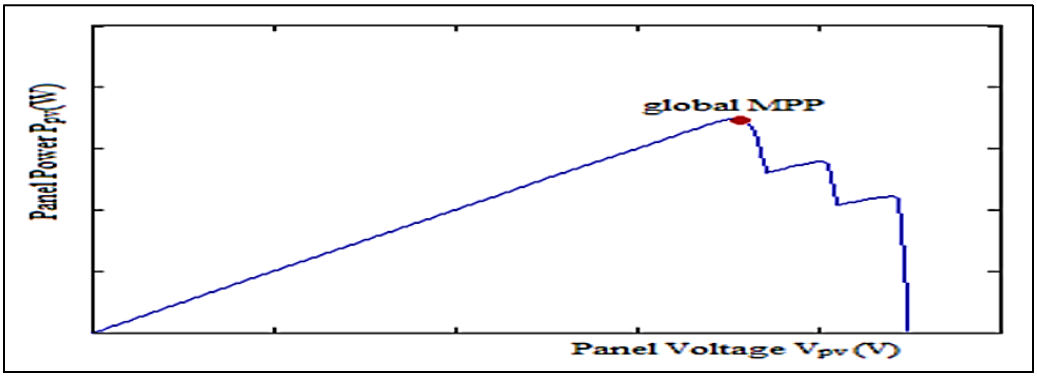


Figure 29: P-V Curves of PV Array Under Partial Shading Condition
Source: Suman, Kumar, Kumar, Babu, and Subhashini (2012)

9.1. Non-Uniform Irradiance of Solar PV Array

The temperature of the PV cells and other external factors like irradiance have significant effects on how well PV solar panels work. There is just one point at which the PV panels' nonlinear electrical characteristics allow for the maximum power to be achieved under uniform conditions. PV panel performance and energy generation can be significantly impacted by non-uniform irradiation. The power loss will rise in direct proportion to the number of shaded cells in a solar PV array with uneven irradiation. Overheating of the shaded cells will occur as a result of non-uniform irradiation. Furthermore, power loss lowers the overall efficiency of the PV system, which in turn lowers energy production (Sethy, 2013). A hotspot issue may arise, and, in a number of situations, the system may be permanently damaged if it is not adequately safeguarded (Upadhyay & Chowdhury, 2014). These issues are addressed by connecting a DC-DC converter to the PV arrays' output (see Figure 30) to serve as a continuous input power load.

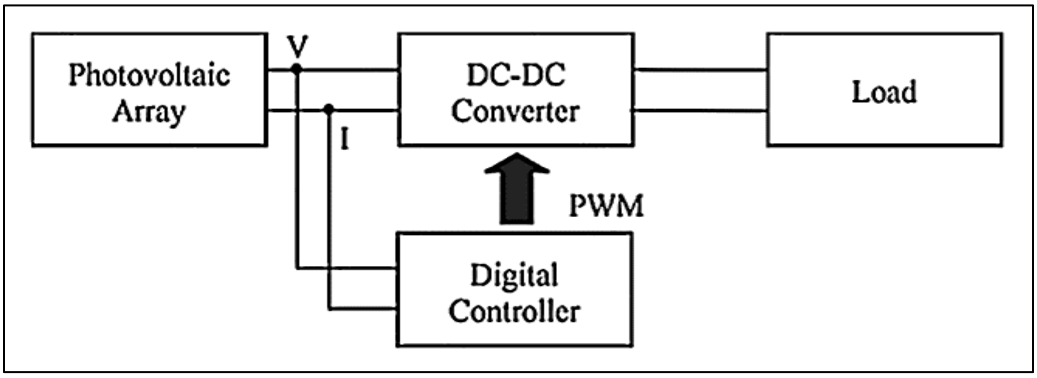
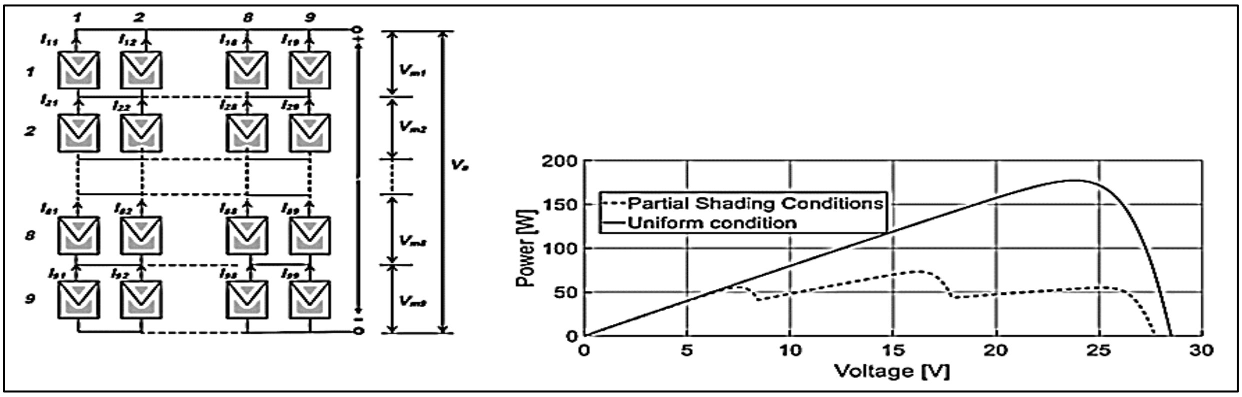


Figure 30: General Block Diagram of An MPPT System

10. Improving Performance of Solar PV Systems Under Partial Shading

A solar PV system would be built by using real PV panels, and measurements would be made for voltages, currents, power, irradiance, and temperature when a partial shading is added, first on one cell, secondly on more than one cell, and then on complete rows and columns. From the collected measurement, an algorithm implementing electrical and probably mechanical devices would be used to alleviate the effect of partial shading. The module configurations that would be used include two standard 33-cell modules. Results will be analyzed, and the best software and hardware system will be selected to alleviate the effect of partial shading. Various module layouts under partial shade conditions will be examined in this study. The optimal setup for mitigating partial shading will be identified, and its impact on the overall stability of the MPPT controller will be examined. Considering that the modules' performance varies according to the irradiation state, the PV modules' output P-V characteristics within the PV array are heterogeneous. The PV array structure and the output P-V characteristic of the PV array manifest in numerous local peaks, as illustrated in Figure (31), due to the intervention of bypass diodes, which modify the electrical connections of traditional total-cross-tied (TCT). Finding and implementing a dynamic system that changes the PV module connections' terminals to spread the irradiance uniformly is necessary to reduce the PV array's irradiance heterogeneity (Nguyen-Duc, Le-Viet, Nguyen-Dang, Dao-Quang, & Bui-Quang, 2022).



(a) (b)

Figure 31: PV Module and Their (A) TCT Configuration, (B) P-V Characteristics Under Uniform Conditions And PSC

Source: Nguyen-Duc et al. (2022)

11. Conclusion

These days, a number of factors, including the rising price of fossil fuels and knowledge of climate change, encourage us to switch to energy-renewable sources. There is also no doubt that solar energy technology will soon reach a more advanced stage thanks to current research. PV energy market share has been growing as a result of the efforts of many governments targeting low CO2 emission; furthermore, the IEA has predicted that by 2050, solar energy will overtake all other sources of electricity worldwide. The scientific basis of a complete PV solar system is presented in this article, starting with the solar cell and its effectiveness and operation. It seems that solar PV applications have a bright future based on the notable developments in solar cell technology over the last few decades.

Authors Contribution

Osama Saad Hamad Saleh: study design, data analysis, critical revision
Kalad Saad Hmad Saleh: data interpretation, write-up
Izzeldin Idris Abdallah: data collection, write-up

Conflict of Interests/Disclosures

The authors declared no potential conflicts of interest w.r.t the research, authorship and/or publication of this article.

References

Alsayid, B. A., Alsadi, S. Y., Jallad, J. S., & Dradi, M. H. (2013). Partial Shading of Pv System Simulation with Experimental Results. *Smart Grid and Renewable Energy, 4*(6), 429-435. doi:https://doi.org/10.4236/sgre.2013.46049

Awasthi, A., Shukla, A. K., M.M, S. R., Dondariya, C., Shukla, K., & Porwal, D. (2020). Review on Sun Tracking Technology in Solar Pv System. *Energy Reports, 6*, 392-405.

Bagher, A. M., Vahid, M. M. A., & Mohsen, M. (2015). Types of Solar Cells and Application. *American Journal of Optics and Photonics, 3*, 94-113.

Bertoluzzi, L., Sanchez, R. S., Liu, L., Lee, J.-W., Mas-Marza, E., Han, H., . . . Bisquert, J. (2015). Cooperative Kinetics of Depolarization in Ch 3 Nh 3 Pbi 3 Perovskite Solar Cells. *Energy & Environmental Science, 8*(3), 910-915.

Bhadoria, U. S., & Narvey, R. (2014). Modeling and Simulation of Pv Arrays under Psc (Partial Shading Conditions). *International Journal of Electronic and Electrical Engineering, 7*, 423-430.

Bowden, S., & Rohatgi, A. (2001). Rapid and Accurate Determination of Series Resistance and Fill Factor Losses in Industrial Silicon Solar Cells. *Proceedings of 17th European PVSEC, Munich*, 1802-1806.

Căluianu, I., Notton, G., Colda, I., Caluianu, S., & Damian, A. (2009). Photovoltaic Energy Generation under Partially Shading Conditions. *Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, ELECTROMOTION 2009*, 1-6.

Dwivedi, A., Bari, A., & Dwivedi, G. (2013). Scope and Application of Solar Thermal Energy in India - a Review. *International Journal of Engineering Research and Technology, 6*, 315-322.

Harjai, A., Bhardwaj, A., & Sandhibigraha, M. (2011). Study of Maximum Power Point Tracking (Mppt) Techniques in a Solar Photovoltaic Array.

Ji, Y. H., Jung, D. Y., Kim, J. G., Kim, J. H., Lee, T. W., & Won, C. Y. (2011). A Real Maximum Power Point Tracking Method for Mismatching Compensation in Pv Array under Partially Shaded Conditions. *IEEE Transactions on Power Electronics, 26*(4), 1001-1009.

King, D. L., Kratochvil, J. A., & Boyson, W. E. (2004). Photovoltaic Array Performance Model. *Technical Report, Sandia National Laboratories, California, USA*.

Liu, C., Wu, B., & Cheung, R. (2004). *Advanced Algorithm for Mppt Control of Photovoltaic Systems*.

Lopez-Varo, P., Bertoluzzi, L., Bisquert, J., Alexe, M., Coll, M., Huang, J., . . . Rosei, F. (2016). Physical Aspects of Ferroelectric Semiconductors for Photovoltaic Solar Energy Conversion. *Physical Report, 653*, 1-40. doi:https://doi.org/10.1016/j.physrep.2016.07.006

Maguire, G. (2023). The Top Global Solar Power Potential Hotspots. *Reuters*.

Mishra, B. (2012). *Matlab Based Modeling of Photovoltaic Array Characteristics.*

Miyatake, M., Veerachary, M., Toriumi, F., Fujii, N., & Ko, H. (2011). Maximum Power Point Tracking of Multiple Photovoltaic Arrays: A Pso Approach. *IEEE Transactions on Aerospace and Electronic Systems, 47*, 367-380.

Nguyen-Duc, T., Le-Viet, T., Nguyen-Dang, D., Dao-Quang, T., & Bui-Quang, M. (2022). Photovoltaic Array Reconfiguration under Partial Shading Conditions Based on Short-Circuit Current Estimated by Convolutional Neural Network. *Energies, 15*, 6341.

Pachpande, S., & Zope, H. (2012). Studying the Effect of Shading on Solar Panel Using Matlab. *International Journal of Science and Applied Information Technology, 1*(2), 2278-3083.

Pandey, A. K., Tyagi, V., Jeyraj, A., Selvaraj, L., Rahim, N., & Tyagi, S. (2016). Recent Advances in Solar Photovoltaic Systems for Emerging Trends and Advanced Applications. *Renewable and Sustainable Energy Reviews, 53*, 859-884.

Pandey, S., Jena, P. K., & Qian, W. (2023). A Review on Maximum Power Point Tracking Techniques for Photovoltaic Systems on the Physical Process and Essence of the Photoelectric Effect. *International Research Journal of Engineering and Technology, 4*(6), 1715. doi:https://doi.org/10.4236/jamp.2023.116104

Ram, J. P., & Rajasekar, N. (2017). A New Global Maximum Power Point Tracking Technique for Solar Photovoltaic (Pv) System under Partial Shading Conditions (Psc). *Energy, 118*, 512-525.

Ramaprabha, R., & Mathur, B. L. (2009). Impact of Partial Shading on Solar Pv Module Containing Series Connected Cells. *International Journal of Recent Trends in Engineering, 2*, 56-60.

Sethy, B. (2013). *Application of Sliding Mode Technology in Pv Maximum Power Point Tracking System.*

Sharma, S., Jain, K., & Sharma, A. (2015). Solar Cells: In Research and Applications: A Review. *Materials Sciences and Applications, 6*, 1145-1155. doi:https://doi.org/10.4236/msa.2015.612113

Singh, J., & Chaturvedi, S. (2016). Iit Jee Physics.

Singh, P. O. (2011). Modeling of Photovoltaic Arrays under Shading Patterns with Reconfigurable Switching and Bypass Diodes.

Sohoni, M. (2012). Engineering Teaching and Research in Iits and Its Impact on India. *Current Science, 102*, 1510-1515.

Sriram, N., & Shahidehpour, M. (2005). *Renewable Biomass Energy*.

Suman, G., Kumar, B. P., Kumar, M. S., Babu, B. C., & Subhashini, K. (2012). *Modeling, Analysis and Design of Synchronous Buck Converter Using State Space Averaging Technique for Pv Energy System*.

Takun, P., Kaitwanidvilai, S., & Jettanasen, C. (2011). *Maximum Power Point Tracking Using Fuzzy Logic Control for Photovoltaic Systems*.

Upadhyay, A., & Chowdhury, A. (2014). Solar Energy Fundamentals and Challenges in Indian Restructured Power Sector. *International Journal of Scientific and Research Publications, 4*, 1-13.

Wikipedia. (2022). *Photovoltaic*.

World, B. (2020). E. S. M. A. Program, Global Photovoltaic Power Potential by Country.

Zhou, W., Yang, H., & Fang, Z. (2007). A Novel Model for Photovoltaic Array Performance Prediction. *Applied Energy, 84*, 1187-1198.