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PV SOLAR GENERATION AND TECHNOLOGIES, COMPARISON OF MONO-SI, POLY-SI AND THIN-FILM PANELS

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PV SOLAR GENERATION AND TECHNOLOGIES, COMPARISON OF MONO-SI, POLY-SI AND THIN-FILM PANELS

By Mahjub Mahmood Hussein HUSSEIN

February 2023

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science

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ABSTRACT

PV SOLAR GENERATION AND TECHNOLOGIES, COMPARISON OF MONO-SI, POLY-SI and THIN-FILM PANELS

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Master of Science in Electrical and Electronics Engineering
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February 2023

Renewable energy is energy derived from natural sources that is replenished at a rate that exceeds what is consumed. Renewable energy sources are abundant, and they are all around us. In contrast, fossil fuels (including gas, oil, and coal) are exhausted over time and require millions of years to create from scratch. Climate change and the increase in fossil fuel prices in the wake of the global increase in energy demand have prompted research to focus on the development of alternative resources. One of the most promising options seems to be solar energy, which can be converted directly into electricity thanks to the PV effect. Solar energy allows for decentralized energy production, which adapts to both resources and local needs and offers significant energy autonomy. A better, more sustainable, and more reliable electrical supply may be achieved by decentralized power generation using renewable energy sources. Solar modules differ in production technology, quality, method of use, and many other parameters. In this project, solar energy, solar modules, and their components will be introduced, and solar cell parameters will be determined. These types will then be compared in terms of efficiency and losses.

2023, 79 pages

Keywords: Clean energy, Solar energy, Solar energy systems, Solar modules.

ÖZET

PV GÜNEŞ ÜRETİM VE TEKNOLOJİLERİ, MONO-SI, POLY-SI VE İNCE FİLM PANELLERİN KARŞILAŞTIRILMASI

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Yenilenebilir enerji, tüketilenden daha fazla bir oranda yenilenen doğal kaynaklardan elde edilen enerjidir. Yenilenebilir enerji kaynakları çoktur ve etrafımızdadır. Buna karşılık, fosil yakıtlar (kömür, petrol ve gaz), tükenen ve oluşması yüz milyonlarca yıl süren yenilenemeyen kaynaklardır. Küresel enerji talebindeki artışın ardından iklim değişikliği ve fosil yakıt fiyatlarının artması, araştırmaları alternatif kaynakların geliştirilmesine odaklanmaya sevk etti. En umut verici seçeneklerden biri, fotovoltaik etki sayesinde doğrudan elektriğe dönüştürülebilen güneş enerjisi gibi görünüyor. Güneş enerjisi, hem kaynaklara hem de yerel ihtiyaçlara uyum sağlayan ve önemli ölçüde enerji özerkliği sunan merkezi olmayan enerji üretimine izin verir. Yenilenebilir enerjilerden merkezi olmayan elektrik üretimi, çevreye saygı gösterirken tüketicilere daha fazla arz güvenliği sağlar. Solar modüller üretim teknolojisi, kalite, kullanım yöntemi ve diğer birçok parametrede farklılık gösterir. Bu projede güneş enerjisi, güneş modülleri ve bileşenleri tanıtılacak, güneş pili parametreleri belirlenecek ve böylece bu tipler verim ve kayıplar açısından karşılaştırılacaktır.

2023, 79 sayfa

Anahtar Kelimeler: Temiz enerji, Güneş enerjisi, Güneş enerjisi sistemleri, Güneş modülleri.

CONTENTS

LIST OF SYMBOLS

I_{SC}	Short-circuit current.
I_{mp}	Current at the maximum point
I_{ph}	photo-generated current
I_{sat}	Diode saturation current
k	Constant of Boltzmann
L_n	Minority-carrier-diffusion length for electrons
L_p	Minority-carrier-diffusion length for holes
q	Electronic charge
R_p	Parallel resistance
Rs	Series resistance
V_{OC}	Open-circuit voltage

LIST OF ABBREVIATION

AlGaInP	Aluminum gallium indium phosphide
AM	Air mass.
a-Si	Amorphous silicon cell.
BOS	Balance of system.
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
C-Si	Crystalline silicon
I-V	Current-voltage characteristic curve
EVA	Ethylene-vinyl-acetate
FF	Fill factor
GaInAs	Gallium indium arsenide
Ge	Germanium
a-Si:H	Hydrogenated amorphous silicon cell.
Mono-Si	Mono crystalline silicon
MPP	Maximum power point
NREL	National renewable energy laboratory
Poly-Si	Polycrystalline silicon
PV	Photovoltaic
P-V	Power-voltage characteristic curve
Si	Silicon
STC	Standard test condition

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1. INTRODUCTION

1.1 General Review

Energy is the basic complication of man in the world of the present, and its sources, the question that the future will ask man. With the declining global stock of hydrocarbons of fossil origin, the ever-increasing demand for energy, and the fear of pollution on an ever-increasing scale, all this has led to the arrival of renewable energies (solar, marine, wind, etc.) at the forefront of global concern today, because their exploitation It meets the increasing demand for energy, and greatly improves the environment. When fossil fuels are used for energy, harmful greenhouse gases like carbon dioxide are emitted. Compared to burning fossil fuels, producing energy from renewable sources results in much less emissions. Switching to renewable energy sources is essential in the fight against global warming since fossil fuels now account for the overwhelming bulk of emissions. (Asmalash and Prakash 2019, Guerra 2017).

The sun is a great source of energy, the Earth receives about 7,000 times more solar energy than all the energy that humanity consumes. It is light energy carried by photons and produced by the hydrogen nuclear fusion reactions that take place inside the sun. Part of this energy can be converted by solar modules into different types (electrical, thermal, mechanical, etc.). Unfortunately, as with most alternative energy resources, their cost is much higher than that produced by fossil fuels. However, thanks to the economic support and incentives provided by local governments, there has been a proliferation of PV systems in recent years, and the cost per watt has decreased significantly in addition to the increase in the efficiency of the PV modules. However, the competitiveness of non-renewable resources remains relatively low in the absence of strong support from society (Gasca 2013, Hafner and Luciani 2022).

Air pollution, global warming, the dangers of nuclear energy, and limited resources have made people realize that economic development that respects the environment is absolutely necessary. Many areas of the world are unlikely to ever be wired for electricity due to the enormous cost of expanding electrical networks to distant, sparsely populated, or inaccessible sites as well as the exponentially growing cost of fuel supply. (Hafner and Luciani 2022).

As solar energy systems become more efficient and less expensive, this will encourage their use separately on an individual basis and stop relying on the national electricity grid. This provides safety from frequent power outages. A large portion of the globe will never have access to electricity due to the high expense of connecting remote, sparsely populated, or inaccessible locations, as well as the rising cost of fuel. (Angadi *et al.* 2019).

Figure 1.1 shows the graphs that show how much solar PV cells will be made around the world from 2010 to 2021.

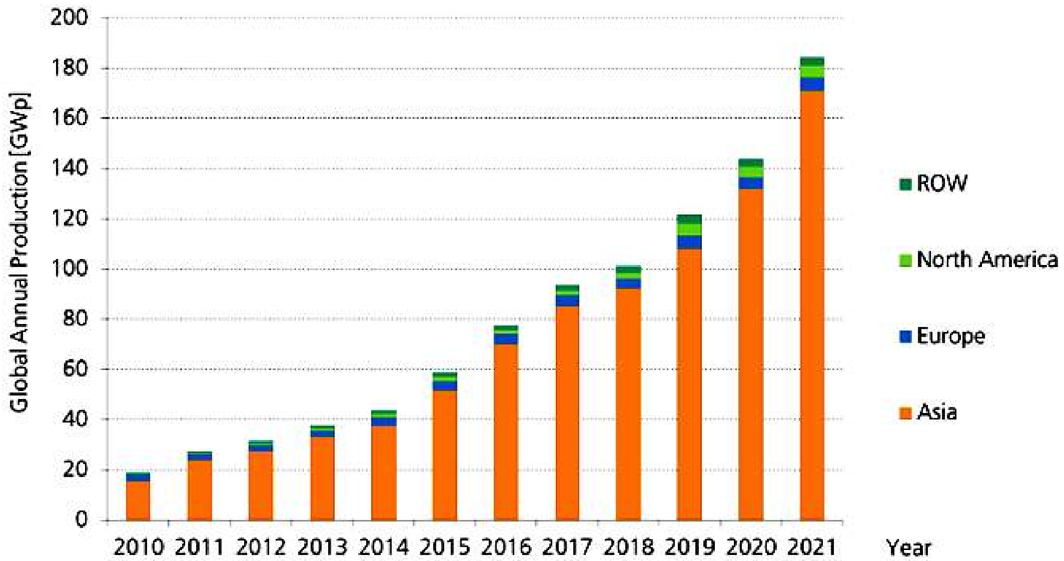


Figure 1.1 Global production of PV modules by region (Feldman *et al.* 2022).

Global PV capacity has grown at an incredible pace during the last ten years, and it will reach 848 GWp by 2021. According to projections, PV production will increase quickly for some years to come. Due to quick advancements in solar cell and module efficiency as well as declining manufacturing costs, this overall capacity has increased significantly. With this accomplishment, it's a fantastic time to assess where the PV sector is and what technology standards must be followed to guarantee the greatest potential effect and momentum in the future. Renewable energy has received widespread attention worldwide, not only because it meets the ever-increasing demand for energy, but also because it provides clean and environmentally friendly means to meet that demand. It seems obvious that energy consumption in the world at present will grow due to the growth of world population and the explosion of industrial development (Feldman *et al.* 2022).

The performance of the PV system has improved greatly, before the year 2000 the typical performance ratio was around 70%, while today it is within 90%. During the past 16 years the material use for Si cells has been significantly reduced from 16 gram/Watt to less than 2.5 gram/Watt due to increased efficiency and thinner wafers as well as larger alloys. The energy payback time for PV systems depends on the geographic location as well as on the technology installed and network efficiency (Alkholidi *et al.* 2019, Wilson *et al.* 2020).

In the past decade, the average efficiency of commercial wafer-based Si modules has increased from about 15% to 20% and more. At the same time, in the measurement laboratory, the efficiency of the CdTe module increased from 9% to 19%. The best performing modules are based on Mono-Si with an efficiency of 24.4% but commercial PV modules are actually much lower. Standard efficiencies show the potential for greater efficiency at the level of production of commercial modules (Gasca 2013).

A module efficiency of up to 38.9% has been achieved by using the capacitor technology. This is with the caveat that the facts and Figure s related to PV energy are changing in terms of efficiency and cost quickly, and the information provided now may soon become outdated again (Feldman *et al.*2022).

The problem of developing solar energy is a global one in nature and is a very urgent task to study. Based on the above, it is clear that any technological solutions that can reduce the cost of solar energy and bring it closer and make it cheaper than the energy generated by conventional methods is very relevant, therefore it is very necessary to monitor even slight changes in the field of technological progress in the solar electricity market in order to Improve the characteristics of solar cells (Angadi *et al.* 2019).

1.2 Solar Energy Technology

Maximum efficiency solar cell development data are supplied from the (NREL, USA). To facilitate discussion, we consider four technology groups, as in Figure 1.2. The first technology group includes solar cells based on compounds of groups III and V of the periodic table, as they are multi-cascade solar cells. It consists of one to five stages, which can be used with or without solar concentrators that focus the sunlight more intensely. According to figure 1.2, today this group has the maximum efficiency. Cascade solar cells are formed either by growing a monolithic multi-stage single-crystal structure, or by mechanical joining of finished elements. (Gasca 2013).

The majority of high-efficiency solar cells belonging to this group are manufactured on the basis of multi-junction heterostructures (Cotal *et al.* 2009). An example of the structure of a three-stage solar cell and an energy scheme for converting solar energy are shown in Figure 1.3.

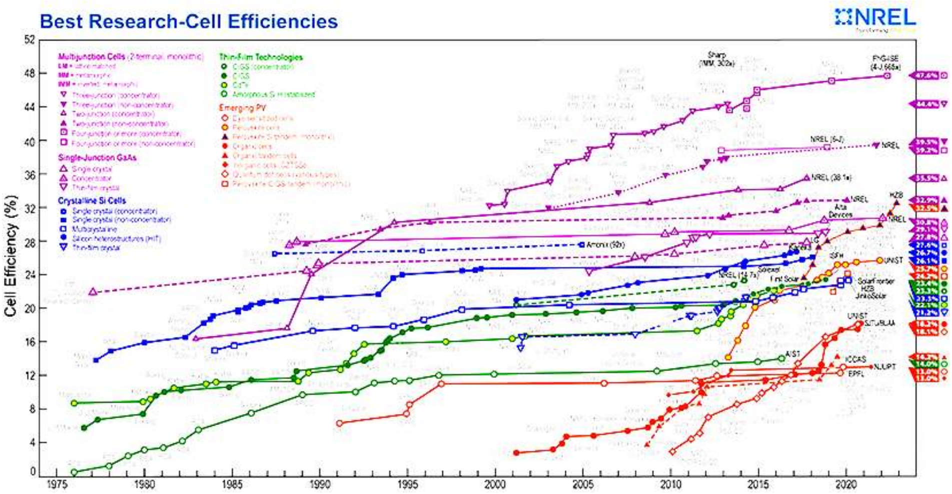


Figure 1.2 Developing solar cells with maximum efficiency for the year 2020 (Data NREL 2022).

The semiconductor junctions of a multi-junction solar cell are often constructed from a Type III-V semiconductor, which is composed of a mixture of Group III and Group V elements. Group III-V materials absorb more light than those in other groups because of their direct bandgap. Silicon (Si), an indirect bandgap semiconductor, has to be 100 µm thick in order to absorb 90% of the light. Conversely, only 1 µm thick GaAs semiconductor can absorb the same amount of light. The possibility of bandgap engineering makes III-V semiconductors superior than conventional Si in many important ways. The elemental composition of III-V materials may be modified to control the band gap and the effectiveness of light conversion (Tanabe, 2009). Gallium (Ga) and indium (In) may be added to or taken out of III-V semiconductors' crystal structures to adjust the band gap and improve optical absorbance (In). Ge creates a current that is about twice as large as the necessary sub-cell current because to its very narrow bandgap. Moreover, it is challenging to lower system prices to a neutral level since a significant portion of production expenses are associated with the Ge substrate (Almosni *et al.* 2018, Jakkala and Kordesch, 2017).

The three connections in each cell are there to form P-N junctions. Because of its 1.81 eV direct band gap, GaInP is utilized for the emitter layer of the top cell, while base GaInAs is used for the emitter layer of the middle cell. The bottom of the Ge cell has an indirect bandgap of 0.67 eV. The p-junction is produced by doping III-V semiconductors with magnesium, zinc, or beryllium impurities, while the n-junction is produced by doping them with tellurium sulfur (Grovenor 1998).

Figure 1.3 (a) depicts a typical three-junction solar cell made up of three stacked p-n junctions made of Ge, GaInP, and GaInAs. Little-resistance tunnel connections are used throughout the assembling process. These connections are produced on a substrate via homogeneous and conjugated supramolecular growth techniques, resulting in a stack of GaInP/GaInAs/Ge. Because of this, the solar-facing sensor's P-N uplink has a wider bandgap energy and can capture light in the blue end of the spectrum. Lower energy photons cross the band gap to reach the lower junction, and they also pass past this obstruction to reach the stack's lowest junction.

The connections between the upper and lower tunnel junctions as well as the upper and middle link pairs are shown in Figure 1.3 (b), a similar electrical circuit diagram of a three-junction solar cell. The three cells are divided by heavy AlGaInP and GaInP doping at the tunnel connections.

The depletion width is reduced when back surface fields (BSF) are used, enabling electrons or holes to tunnel through while preventing charge carriers from scattering. Tunneling diodes may provide ohmic connections between cells while being optically transparent and having a low resistance, decreasing parasitic absorption, by enabling electrons to pass through the layer (Luque and Hegedus, 2011)

The semiconductor layers of a three-junction solar cell are built between two contacts; the front contact is a low-resistance electrode that makes it easier to collect current. Because to its wide availability and low cost, aluminum (Al) is used in commercial three-junction solar cells, while silver (Ag) is used in standard test cells but is more costly. If a metal grid comprised of aluminum (Al) or silver (Ag) is put on top of a solar module, shading losses may increase. Transparent conductive oxides (TCO) are used as a replacement electrode in three-junction solar cells due to their very transparent layer. It also creates an ohmic link to the top contact layer of the cell, which improves the performance of the current ensemble (Kao *et al.* 2019).

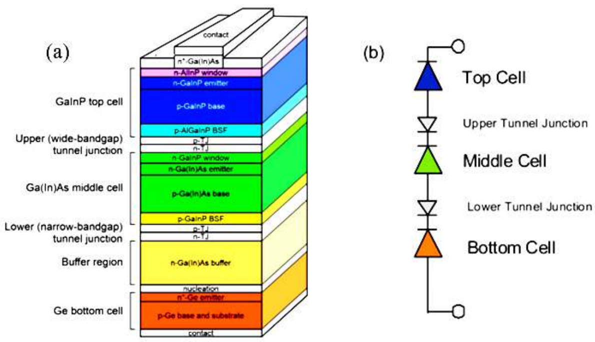


Figure 1.3 (a) Schematic of a monolithic three-junction solar cell that has been epitaxially formed on a substrate. (b) Diagram of an equivalent electrical circuit. (Cotal *et al*. 2009).

However, focusing sunlight on the solar cell using condensers (Fresnel lenses) to obtain high efficiency, although it is effective and increases the efficiency of solar modules by up to 40%, it is expensive and sometimes requires tracking the sun and cooling the PV modules, especially if they are of medium or high concentration. It must be remembered that in standard laboratory PV elements are examined under special lighting conditions. Multi-stage solar cells, when used under natural conditions, have poor performance when illuminated with scattered light, require the use of mechanically complex support structures, including tracking circuits, and require efficient cooling of the structure due to heating (Angadi et al. 2019). In the lab, highly concentrated multi-junction solar cells achieve efficiencies of up to 47.1% today. The disadvantages of obtaining multi-stage solar cells are the use of expensive equipment, single-crystal Ge substrates, GaAs, and other basic materials and components and the complexity of the technological process (Cotal *et al*. 2009).

The first technology group has a maximum efficiency of 27.5%, however, this is slightly higher than Si (25.6%). The main disadvantage of this group is the high cost. As it requires a more complex technological process, and high prices for materials and equipment, which increases the price of the generated electrical energy (Feldman *et al*.2022).

The second technological group includes solar cells manufactured on the basis of Si technologies. As mentioned earlier, Si is currently the main material for PV solar energy, on the basis of which more than 90% of solar cells are manufactured. The high rate of development of the PV industry forces high-purity Si manufacturers to pay more attention to the research and development of its production processes. As a general rule, Si for PV solar cell is obtained by the method known as Siemens process which is based on chemical vapor deposition (Gribov and Zinov'ev 2008, Maronchuk *et al*. 2015). Technological methods and processes of this group are the most advanced and we will not focus on them.

The purpose of this paper is to provide a brief description of the main aspects related to the implementation of the global solar PV industry, to study solar cells belonging to different technology groups, to evaluate their advantages and disadvantages, and their production characteristics. Besides, a comparison of the calculated and measured photoelectric features will be performed. Finally, the results will be presented using a graphical user interface in Matlab.

1.3 The Aim of Thesis

The main goal of this research is to invest solar energy and convert it into electrical energy using solar modules to carry out this conversion process. Also, this research studies both the structure and installation of solar modules by identifying their fundamental elements and the properties of these physical elements which will be used to make a comparison between different types of solar modules.

1.4 Thesis Outlines

This thesis includes eight sections, as follows:

Section1: Present a general introduction.

Section2: Study the different types of semiconductor junctions, which are the prime components in any solar cell.

Section3: Introduce the solar modules types (their construction, advantages, and disadvantages).

Section4: Build the mathematical model of the PV equivalent circuit.

Section5: Define the solar cell parameters such as the external solar cell parameters, the voltages and currents in the open and short circuit, respectively, and finally, the conversion efficiency.

Section6: Introduce the types of PV systems along with their basic components.

Section7: The experimental results are presented using a graphical user interface (GUI) in Matlab.

Section8: It includes conclusions and recommendations on determining the best of the three types of solar modules available in the market today.

2. SEMICONDUCTOR JUNCTIONS

Metals are normally excellent at carrying current and insulators at restricting it. Semiconductors are intended to convey current in certain situations and block it in others. This exceptional characteristic has wide-ranging repercussions. The majority of technological wonders from the previous century, as well as those we see now, are thanks to semiconductor devices, which are used with a variety of sensors like transistors (there are billions of them in a single modern computer processor), solar cells, and diodes.

In the material spectrum, semiconductors are situated halfway between insulators and metals. There seems to be a reasonably small bandgap that enables thermal or visible light to activate electrons. Additionally, tiny extra electrons or holes from other atoms may be "doped" into semiconductors. By altering the density of free charge carriers, doping makes it possible to modify the conductivity of the material by several orders of magnitude.

Scientists have studied a broad range of semiconductors throughout the years. Group 4 contains two of the most well-known elements, Si and Ge. Yet, since gallium (III) and arsenide (V) include atoms from two different elements, semiconductors like these are more complicated (V). While doped semiconductors are less frequent than pure ones, they do occur (which makes it possible to control its resistance). In practically all solar cells, junctions made of rare materials doped with various chemicals are employed. C-Si and the p-n junction are both made in the same semiconductor fabric (Wang 2020).

By combining two semiconductors with radically differing chemical characteristics, the heterojunction is created. A p-i-n junction's electric field is increased by the existence of an intrinsic I layer if one exists there between the p-type and n-type layers (which acts as a capacitor). Another kind of junction is the "MS junction," which is the junction of a metal and a semiconductor (Wilson *et al.* 2020).

2.1 The p-n Junction in the Dark

In several studties, concentrate on the most common kind of PV cell, which includes a p-n junction, cathode, and anode, however there are many additional types (multi-junction cells, bifacial cells, etc.). A photovoltaic cell is a device that employs the photoelectric effect to generate an electric current by using a p-n junction made from a high-purity material (often Si). It has a p-type neutral zone on the side that was doped with trivalent impurities, and an n-type neutral area on the side that was doped with pentavalent impurities (Marius 2016). For n-Si doping, phosphorus is often used, leading to an electron surplus in the n-type neutral region. In p-type doping, boron is often employed to increase the number of holes in the p-type neutral zone; however, electrons in the valence band may readily fall into this gap, generating additional holes that improve conduction. When the donor electron's energy is thus near to the conduction bands, electron conduction occurs (conductivity increases). Electrons go from the n to the p substrate, while holes move in the other direction (Marius 2016). Diffusion results in a net charge at the junction that is positive on the n side and negative on the p side. There is a region of varying voltage between the parts as a consequence. Due to the contact electric field and the device's varying dope, which prevents further carrier diffusion until equilibrium is reached. Electron and hole diffusion causes the depletion zone, also called the space charge area, and the diffusion current (Hu 2009, Aribisala 2013).

To contrast the surplus of electrons in n-type semiconductors, p-type semiconductors contain an abundance of holes. Carriers are allowed to shift their weight freely from one side to the other until equilibrium is reached. In Figure 2.1, the conduction band and holes are shown in orange, while the valence band and electrons are shown in blue, to illustrate how the p-n junction diode operates when the light is turned off. The diode acts as a one-way diode with respect to charge carriers; with a reverse bias, a negative voltage applied to the p-type side keeps propagation unfavorable and the current low. Ideally, there would be no current flow, and reverse bias would expand the depletion regions. By applying a positive voltage to the p-type side of the junction, we may reduce the internal field and allow many carriers to go over the interface, resulting in a large current (forward bias). The current exponentially increases with increasing positive voltage but remains negligible when it is negative. When the forward bias causes the depletion zone to decrease in size, the diffusion current grows exponentially.

When the circuit is in equilibrium, there is no net current. Like electron drift current and electron diffusion current, hole drift current and hole diffusion current are in perfect equilibrium with one another (Jean *et al.* 2015, Li 2022).

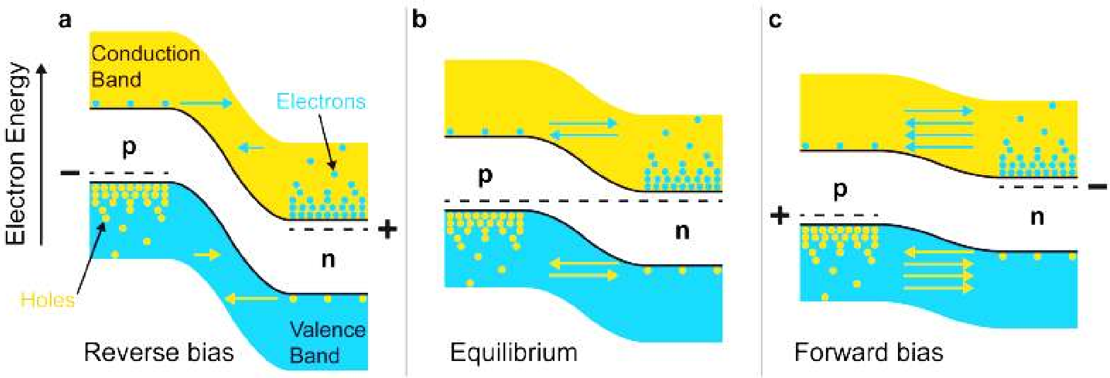


Figure 2.1 An energy band diagram of a p-n junction diode showing (a) reverse bias, (b) equilibrium, and (c) forward bias conditions (Jean *et al* 2015).

2.2 The p-n Junction under Illumination

A solar cell is only a diode that can generate free electrons and holes by absorbing light, but not all materials can be used to make them. This can only happen when matter absorbs photons with an energy greater than or equal to its energy gap, producing electron-hole pairs, as the main purpose is to produce electricity from the visible spectrum of the sun (Tala-Ighil 2015). The photoelectric effect causes a material to emit electrons when it is exposed to a stream of photons (visible or ultraviolet light in general). This is due to the possibility that photons might force electrons to move from the valence band to the conduction band after absorbing them (Kazi 2021).

As seen in Figure 2.2 below, when the p-n junction is lit, more electron-hole pairs are produced in the semiconductor. The diffusion process causes a positive charge to be formed on the n side and a negative charge to be generated on the p side of the junction.

Substantial increases in the number of holes and electrons are seen in the n-type and p-type regions, respectively. Due to the higher electron and hole densities, it is now possible for them to easily transition from the depletion region into the quasi-neutral zones. P-type holes enter the n-type region when electrons leave it. The electrons in this instance go from the n-region to the load, where they were produced, through the negative conductor, the metal contacts, and eventually into the battery. After rejoining the holes in the p-region, the electrons go back to the anode, the positive contact site. (Li, 2022; Safitri *et al.*, 2019; Smith *et al.,* 2018).

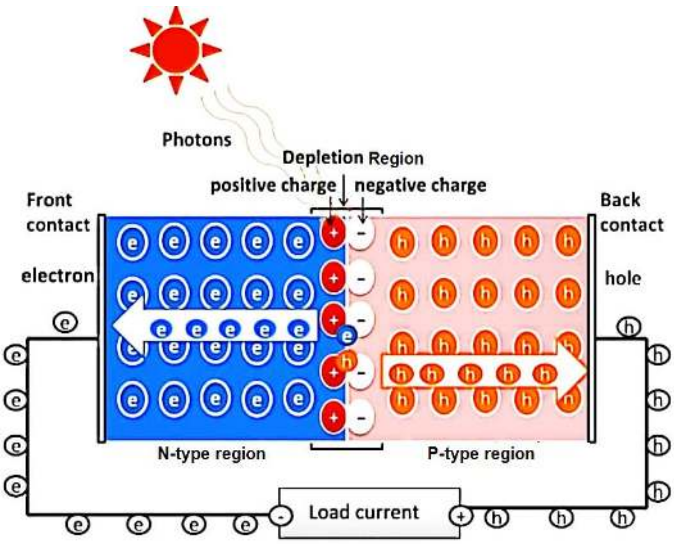


Figure 2.2 A p-n junction schematic demonstrating the photovoltaic effect, which generates current when exposed to sunlight (Kazi 2021).

For an excited electron to be promoted from the valence shell to the conduction shell, it is necessary that the energy of the photon that hits that electron exceeds a threshold value. This minimum energy value is called band gap energy (BandGap), and is characteristic of the material with which it works. In order to determine which materials are the best to benefit from this phenomenon, it is necessary to study which of them is capable of making the most of the photons of solar radiation that fall on the Earth's surface (Berney 2014).

Excessive thermalization, or the loss of energy as heat, is the consequence of overshooting the bandgap. Low-energy photons are reflected rather than absorbed because an electron cannot be moved from the valence band to the conduction band if the input photon has less energy than the bandgap energy. Look at Figure 2.3. For best effectiveness and power collection, the band gap structure should be tuned to absorb as many photons from the sun's spectrum as is practical. (Kazi 2021).

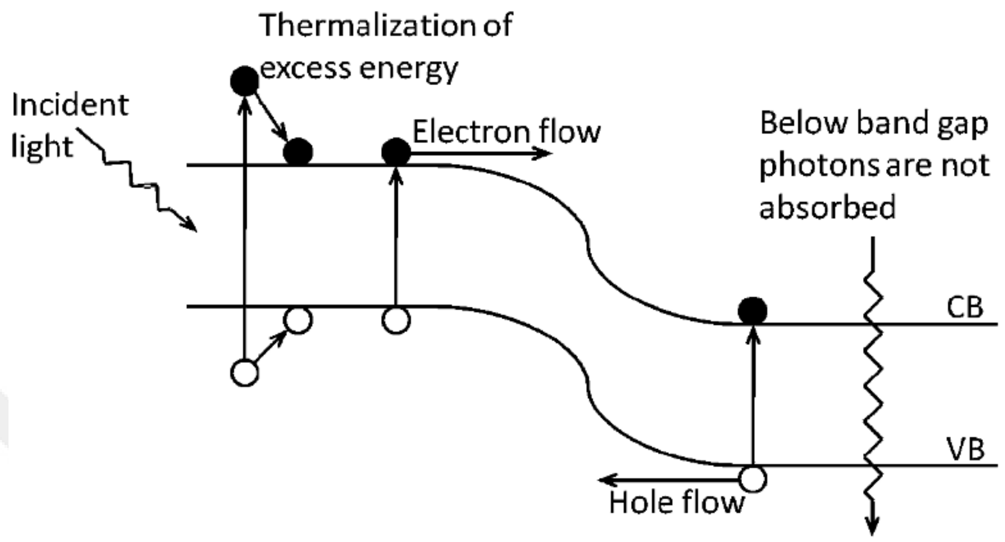


Figure 2.3 Band (energy) diagram of a p-n junction, demonstrating the effects for incident photon energies (Weisse 2010).

No net current can flow to the p-n junction under the open circuit situation (where there is no external connection between the n-type and p-type regions). This implies that the opposing recombination current is required to balance out the current caused by the flux created by photo- and thermo-generated carriers. A current is created across the PV cell when it is lighted and coupled to a load. (Al-Ezzi and Ansari 2022, Hu *et al*. 2021).

Equation below, describes the behavior of the p-n junction of an ideal solar cell:

$$I = I_{ph} - I_{sat}[exp(\frac{qV}{KT}) - 1] \quad (2.1)$$

Where I output current, I_{ph} photocurrent, I_{sat} diode saturation current, V the voltage between the two terminals of p-n ideal diode, electron charge (1.6×10^{-19} C), k Boltzmann's constant = (1.38×10^{-23} J/K), T is the cell temperature in Kelvin.

$$I_{ph} = qAG(L_N + W + L_p) \qquad (2.2)$$

Where, L_N and L_p are the minority carrier diffusion lengths for electron and holes respectively, W is the width of the depletion layer, G is the diode electron-hole pair generation rate, A is the total illuminated cross sectional area of the device.

3. TYPES OF SOLAR MODULES

3.1 Introduction

Many consumers and organizations are looking for technology that offers lower costs, higher efficiency, and greater reliability, due to economic, inflation and environmental. Due to the emergence of many unconventional materials, manufacturing methods, and technologies involved in the manufacturing process of working PV cells, PV materials and technologies can be categorized into three major generations, are as follows:

First generation: This generation is based on P-N bulk material junction and includes PV technologies based on Mono-Si and Poly-Si.

Second generation: This generation is based on the development of thin-film technology as well as the use of different materials ((a-Si), (CIGS), (CdTe), etc.).

Third generation: This generation is highly efficient because it is based on newer chemical compounds. In addition, to harvest the solar spectrum more efficiently, multiple energy levels are used.

There are many solar modules available in the market. Basically, customers are attracted by the low price, claiming that the technical parameters are almost the same for different solar modules. Just like with other products, buyers want the deal that offers lower costs and higher efficiency, but often they sacrifice quality at the expense of price (Pastuszak and Węgierek 2022).

A decrease in product quality can be at the cost of the solar energy system's efficiency and its default life. In order to know reliable information about the reliability and efficiency of these solar modules, this section has come up with a small guide for users, which will help in obtaining a lot of necessary information about the types of solar modules. The main-types of solar cells that are now widely sold in the domestic market are as follows:

1) C-Si cells: Si cells are the most common. They have good efficiency but are more expensive compared to thin-film cells. They are divided into 2:

a. Mono-Si: Mono -Si wafers are cut into slices of a large single crystal ingot, in a relatively expensive process. They are very efficient and also expensive.

b. Poly-Si: They are cheaper than crystalline mono, wafers can be obtained from different techniques.

2) Thin-film cells: They have a cheaper and less efficient manufacturing process than C-Si. It can be divided into:

a. a-Si: These cells are much thinner and absorb light more effectively compared to C-Si.

b. CdTe: These PV modules have good response to low coefficients of light and temperature, and have high throughput over a wide range of climatic conditions. CdTe modules are well established in the PV module industry (Angadi et al. 2019).

c. CIS/CIGS: CIGS is a semiconductor that absorbs light more efficiently than C-Si, but these PV modules require a thicker film than that of the a-Si PV module (Plants 2015).

d. Hetero-bonding with a complex thin-film (HIT): This type of solar cell consists of a single Si wafer surrounded by very thin layers of a-Si. They are considered more efficient than typical crystalline units, but are more expensive (Guerra 2017). Figure 3.1 below shows the different types of PV cells:

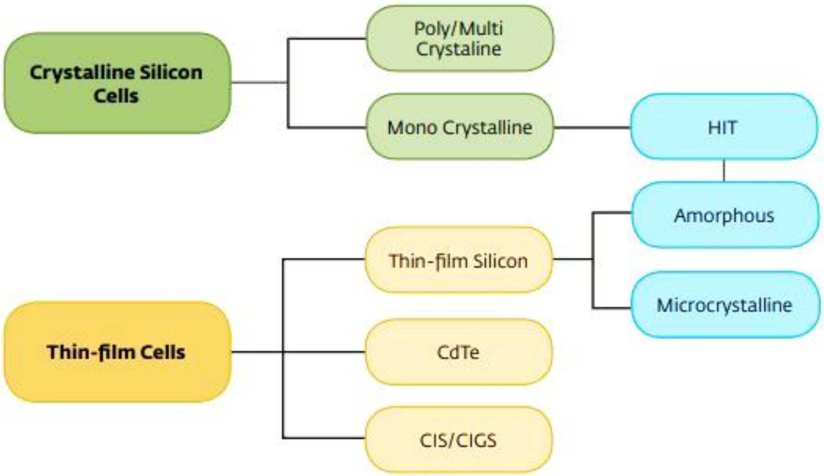


Figure 3.1 Types of PV cells (Guerra 2017)

3.2 Crystalline Silicon Solar Cells

This is the first generation of solar cells, C-Si is a semiconductor material that has a bandwidth of about 1.12 eV at 300 K. The band gap value in wavelength is about 1107 nm, but it has indirect electronic transmission. This means that a photon is less likely to pass the bandgap and excite a valence band electron, which makes this material have a lower absorption coefficient than other semiconductor materials with current PV applications, which have direct electron transmission.

Current market share is held by PV cells made from C-Si, with Si-Wafer-based PV technology expected to account for more than 95% of global output by 2021. Around 84% of all C-Si output was accounted for by the mono-Si method. It is anticipated that C-Si solar cells will play a significant role in the PV business going forward (Pastuszak and Wiegierek 2022). The typical cell efficiency for monocrystalline silicon in a laboratory is 26.7% for single crystals and 24.4% for polysilicon wafer-based technology. From about 15% to 20% or more, the average efficiency of commercial wafer-based Si modules has grown significantly during the previous decade. Increased manufacturing efficiency is a real possibility, as shown by these benchmark skills (Muhammad *et al.* 2019, Richter *et al.* 2013).Despite the fact that certain high-efficiency cells may achieve efficiencies of more than 20%, the vast majority of commercial cells are still only capable of 15–18% efficiencies. Ninety-four percent of the world's C-Si PV modules were manufactured by Asian factories in 2021. To the tune of 75%, China (the largest manufacturer) was in the driver's seat. The contribution from Europe was 1%. U.S. and Canada, by 3%.Silicon (Si) accounts for 26% of the crustal material on Earth's surface, making it one of the most plentiful resources and a safe element for the environment. The Si solar cell stands out among the other kinds of solar cells in the PV industry because Si is both abundant and safe to use as a resource. The Si PV cell is the most useful and widely made way to meet the growing demand for PV energy around the world (Wagner 2021). An example of a semiconductor device based on Si is the complementary-Si (C-Si) photocell. It has the same semiconductor structure as a conventional diode. High-efficiency solar cells with low manufacturing and processing costs are now the most pressing technological challenge for solar cell producers. Reducing the high cost of producing C-Si substrates, which are used in the fabrication of Si solar cell modules, is crucial. The crystalline solar cells used in the first generation are divided into two broad categories of photovoltaic (PV) modules. These two varieties now account for the vast majority of solar cells sold worldwide. These are the two types of solar panels:The first variety, known as Mono-Si, is a crystalline solid in which the crystalline lattice is continuous, unbroken, and free of grain boundaries over the whole mass (including the periphery). A single crystalline solar cell is used in this kind of solar module. A complicated method is used to generate mono-Si, which results in high-purity, ultra-thin sheets with smooth edges. This Si variety is ideal for use in solar module production because of its high efficiency in the photovoltaic (PV) effect, the process by which sunlight is transformed into electricity (Eldin et al. 2015).The second form is called multi-C-Si, or Poly-Si for short, and it consists of several tiny crystalline grains that are all facing in different directions. In contrast to poly-uniformly colored Si wafers, mono-varying Si's grain sizes are easily discernible. Lattice mismatches at grain boundaries cause several problems. The charge carrier lifetime of Poly-Si is shorter than that of Mono-Si. If the grain boundaries of a material are too large, the charge carriers in it will die sooner. Making a block of Si and then cutting it into sheets with correct angles is the simplest way to generate poly-Si. There is no need for further processing to remove the contaminants after all the silicon has been condensed into a big mass. Figure 3.2 depicts the aforementioned. (Wagner 2021, Luceo-Sánchez *et al.* 2019)

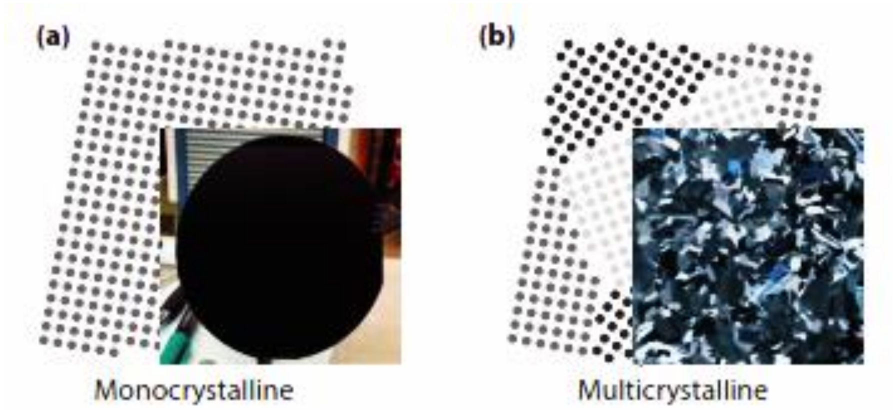


Figure 3.2 Schematic of the atomic structure of Si (a) Mono-Si, (b) Poly-Si (Jäger *et al.* 2016).

3.3 Mono-Si vs Poly-Si Solar modules

- Mono-Si vs. Poly-Si Solar Modules

- Mono-Si Solar cell/module

Cutting the pure Si ingot will result in square wafers with rounded edges, because the pure Si ingot has a round shape, and this creates small openings between the cells when they are assembled into a PV module. Also, it has a uniform dark appearance due to the fact that it is made of pure Si and because of the way light interacts with the pure Si.

- Poly-Si solar cell/module

In contrast to the uniform dark appearance of Mono-Si solar cells, because of the way sunlight interacts with Poly-Si solar cells, Poly-Si cells tend to have a blue shade. In addition, because Poly-Si wafers are not cut from cylinders like Mono-Si ones, their edges will not be rounded. Thus, they can be easily identified by the absence of rounded edges and their bluish color (Ayadi *et al* 2022).

- Mono-Si vs. Poly-Si Solar Modules Efficiency

- Mono-Si solar module

As compared to other kinds of solar modules, commercial Mono-Si cells have the best efficiency (around 15-20%; this percentage is projected to grow in the future). Despite Mono-superior Si's efficiency, the gap between it and Poly-Si cells in the commercial market is now rather narrow, making the former moot (Ayadi *et al.* 2022).

- Poly-Si solar module

Almost all commercial Poly-Si solar have efficiencies between 13% and 16%, which is very good but unlikely to rise in the future. A Poly-Si cell consists of a lot of crystals, so the efficiency of energy production decreases as a result of a lack of free space for electrons (Muhammad *et al.* 2019).

- Mono-Si vs. Poly-Si Temperature Coefficient

- Mono-Si solar module

The temperature coefficient of almost all Mono-Si solar cells falls within the range (-0.3%/C to -0.5%/C). Hence, the efficiency of a Mono-Si solar cell momentarily drops by 0.3% to 0.5% when the temperature of the solar modules is elevated above 25°C (standard test temperature) by 1°C (32°F).

- Poly-Si solar module

The temperature coefficient of poly-Si PV cells is greater than that of mono-Si cells. Hence, Poly-Si modules are not suited for usage in hot conditions since their efficiency drops dramatically as the temperature increases. (Thirunavukkarasu *et al.* 2021, Capitaine et al. 2021, Huot *et al*. 2021).

- Life expectancy

- Mono-Si solar module

A yearly efficiency loss of 0.3% to 0.8% is typical for mono-Si PV modules. Let's assume that the deterioration rate of a mono-Si solar module is 0.5%. As a result, after 10 years, the system will function at 95% maximum efficiency, after twenty years, at 90% maximum efficiency, and so on, until the PV system loses a significant percentage of its energy production potential. If the efficiency drop keeps happening at about the same pace, PV modules will stop working. The majority of mono-Si solar modules have a 25- or 30-year warranty period. The lifespan of the system is estimated to be at least 40 years. (Muhammad et al. 2019).

- Poly-Si solar module

The deterioration rate of poly-Si PV cells is somewhat greater than that of mono-Si PV cells. As a result, their efficiency degrades somewhat more rapidly than mono-Si cells. However, the system can last from 20 to 35 years and sometimes more. (Ouédraogo 2021).

The following Table 3.1 provides a summary of the aforementioned comparison

Table 3.1 A comparison between Mono-Si and Poly-Si solar modules.

Type of solar module	**Mono-Si**	**Poly-Si**
Type of Material	Single Pure Si Crystal	Different Si Fragments Molten Together
Appearance feature	Uniform dark squares with rounded edges	Blue squares with no rounded edge
Conversion Efficiency	15%- 20%	13%- 16%
Space Efficiency	Good Efficiency	Less Efficient
Temperature Coefficient	-0.3% / °C, -0.5% / °C	-0.3% / °C, -1% / °C
Lifespan	Almost 40 years	Almost 35 years
The Recyclability	Yes	Yes
Price	$$$	$$

3.4 Thin-Film Solar Modules

The main focus of this new generation of PVs was to reduce production costs, by relying on cheap and low-quality materials. Thin-film technologies rely on the deposition of materials on inexpensive, light and flexible substrates. It includes (a-Si), (CdTe), (CIGS), etc. (Eldin *et al.* 2015, Safitri *et al.* 2019).

The process of assembling C-Si solar cells into modules differs greatly from the process used to assemble thin-film modules. With C-Si technology, the procedures for making solar cells and PV modules are distinct, but in thin-film technology, they must be carried out concurrently. A transparent front contact, a stack of active layers containing one or more semiconductor junctions, and a metallic rear contact must all be deposited before such a module can be built. Due to the high throughput needed, the size of the plates may be significantly bigger than 1 m2 when these layers are applied to glass plates for mass production. The solar cell that results from placing such a layer stack onto a large glass plate has the potential to be highly effective and provide a sizable current (Moon *et al.* 2016). Due to the fact that all current would need to be passed via the front and back contacts, both of which are relatively thin, the module's resistive losses are much higher than they are in C-Si modules. A number of microscopic cells, each around 1 cm wide and as long as the module itself, are formed into the module. The cells are connected in a sequence along the width of the module. The extreme left and right metal busbars of the module collect the current and transport it to the base, where it is connected to external wires (Jäger *et al.* 2016, Sampaio and González 2017).

Cell efficiencies of 5-7% for two-junction designs and 8-10% for triple-junction designs are possible using the most common kind of thin film technology, amorphous solar cells (a-Si), but they are also more fragile. To create a-Si:H, hydrogen must be doped into the material (Almosni *et al.* 2018).

As the layer thickness decreases over time, and since using a-Si:H in sunlight might cause it to degrade and produce operational concerns over time, thicker layers will be necessary to ensure long-term functioning. Single-junction and multi-junction devices with high efficiency and stability have been developed, nevertheless. Microcrystalline Si (uC-Si) may be made if the process involves a large amount of H, which makes the material more stable in the presence of solar radiation and reduces the number of defects compared to a-Si. Standard laboratory efficiencies for microcrystalline Si cells (uC-Si) range from 11.9% for single-junction cells to up to 14.0% for multi-junction cells (Gruginski *et al.* 2021).

There have been significant improvements in manufacturing processes, material quality and hardware design in recent years, but the rate of improvement in cell efficiency appears to have stabilized. It is widely accepted that multi-link devices are required if one wants to achieve any tangible efficiency improvement. In a three-link structure, 13% global standard efficiency was achieved. While previously best stable efficiency was 11.8% (Karzazi and Arbouch, 2014).

To deposit a-Si, the substrate is typically heated to between 150 and 300 °C, and the PECVD technique is used to improve the chemical vapor deposition using plasma. Because of its disordered structure, a-Si has a much larger band gap than mono-Si (1.7 eV) and can absorb 40 times as much light as mono-Si. Solar cells that are both flexible and lightweight may be made practical by using a 300-nm layer of a-Si:H, which can absorb 90% of the higher bandgap photons in a single pass. Most cutting-edge commercial cells now use multi-junction a-Si:H modules. Commercial adoption is hindered by photodegradability and decreased efficiency, Although a-Si:H cells are well suited for low-power, small-volume applications, and although Si is inexpensive, plentiful, and non-toxic, market adoption on it is relatively limited, due to its lower efficiency and photodegradability compared to other thin-film cells (Jean *et al.* 2015, Almosni *et al.* 2018).

Figure 3.3 is a schematic representation of a low-cost and straightforward to manufacture a-Si PV cell. A solar cell made from Si has less efficiency than one made from another material because the charge carriers it generates are less organized. Typically, aluminum is used to provide a reflective conductive layer that serves as the rear contact, while transparent conductive oxide (TCO) is used to create a reliable front contact. The p-i-n junction is the backbone of most thin-film (a-Si) PVs. Three layers of amorphous silicon—a p-layer (p-doped), an i-layer (un-doped substrate), and an n-layer—are grown on a substrate made of common glass (n-doped). These coatings are produced via PECVD of hydrogen and silane gas in a plasma environment.

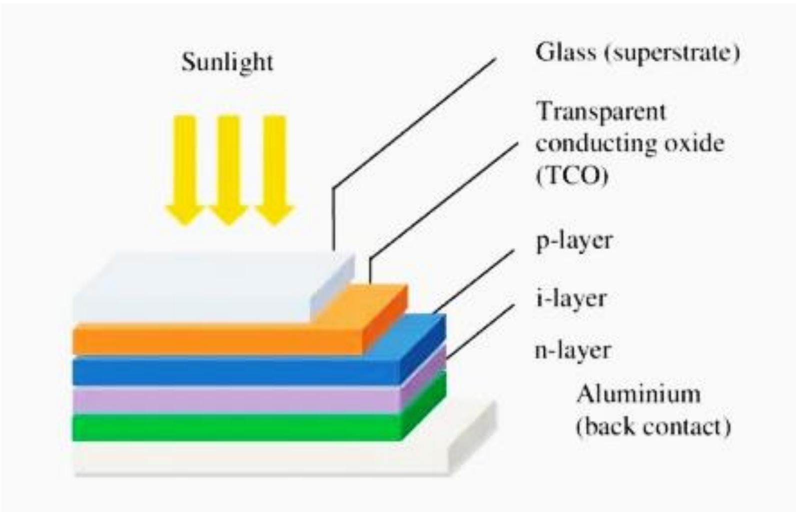


Figure 3.3 Schematic of (a-Si) cell structure (Karzazi and Arbouch 2014).

Thin-film PV modules have a far reduced likelihood of breaking and don't have the same manufacturing problems as crystalline solar cells, but their efficiency is much lower.

Others are concerned that the materials could have a negative environmental impact both during manufacture and after disposal. Amorphous solar cells provide a lot of placement flexibility; they may be installed over relatively light objects like fabrics, backpacks, and the like, and need less support when placed atop roofs.

3.5 Crystalline Silicon vs Thin-Films Modules

Due to the lower Si consumption and simpler manufacturing technology, thin-film modules are generally cheaper than crystalline modules. However, the price difference is not very big, the price of crystalline solar modules has dropped a lot in recent years. The difference in price is decreasing and the effectiveness of both technologies is rapidly increasing. (Jean *et al* 2015, Cuervo 2012).

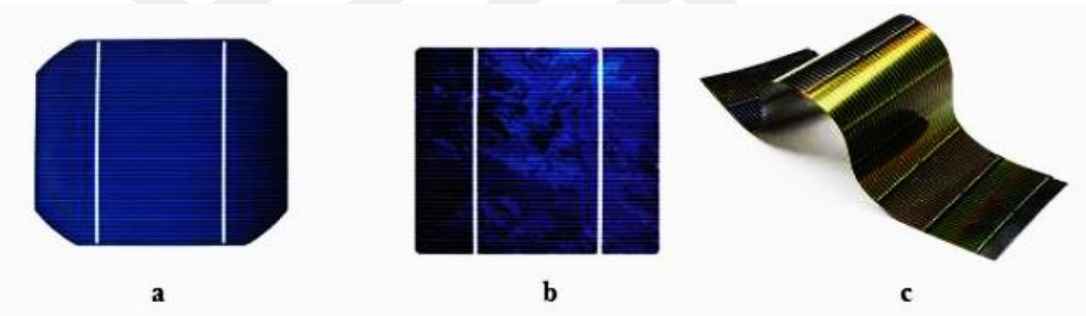


Figure 3.4 (a) Mono-Si solar cell, (b) Poly-Si solar cell, (c) Thin-film cell (Karzazi and Arbouch 2014).

It is important for end users and installers to keep in mind some important considerations that come into play when designing a solar power plant based on different types of solar cells. Based on this information, the designer can decide which solar cell technology - thin-film or crystalline - is best for a particular project. The table below provides a very brief comparison of the two technologies. When selecting modules for a particular project, there are many other things to consider as well.

Table 3.2 C-Si and Thin-film modules comparison.

Technology Used	C-Si modules	Thin-film modules
Varieties of technology	Mono-Si, Poly-Si	(a-Si), (CdTe), (CIGS)
Ratio of voltage at operating point to open circuit voltage (Vmp/Voc) (higher is better as there is less difference between Voc and Vmp)	80% to 85%	72% to 78%
Temperature coefficients (low temperature coefficient is better when operating at high ambient temperatures)	higher (-0.4-0.5%/degree)	lower (-0.1-0.2%/degree)
Filling of the current-voltage characteristic (ideal element has 100% filling)	73% - 82%	60% - 68%
Module design	framed in anodized aluminum	without frame between 2 modules – lower price, more weight on a flexible base - lighter, cheaper
Module efficiency	13% - 19%	4% - 12%
Compatible with inverters	The lower the temperature coefficient, the better. Transformer less inverters can be used	The designer must consider factors such as temperature coefficient, Voc/Vmp ratio, insulation resistance, etc. Typically, thin-film modules require an isolated inverter
Mounting structures	Typical	In many cases the installation cost is much less
DC connections	Typical	Typical, sometimes more splitters and fuses may be required
Typical Application	Residential/Commercial/Generation to Grid	Residential/Commercial/ Generation to Grid
Required area	about 150 W/m2	may require up to 50% more area for the same solar power

Table 3.2 C-Si and Thin-film modules comparison. (Continued)

Technology Used	C-Si modules	Thin-film modules
Highest recorded efficiency	Mono-Si 26.7% Poly-Si 24.4%	(a-Si) 14.0%, (CIGS) 23.4%, (CdTe) 22.1%
Market Share	93%	7%

In general, more power per area can be obtained by using Mono-Si modules due to the higher efficiency of these PV modules. But if you compare modules of the same power (regardless of area), there is no definitive answer. A lot depends on the solar cell manufacturer - the better the solar cell, the better it works and generates more energy (Ayadi *et al* 2022, Cuervo 2012).

The larger and purer the Si crystal that makes up the solar cell, the more efficient it is. As a result, single crystalline modules are about 10-15% more efficient than Poly-Si modules of the same size. On the other hand, Poly-Si modules are often described as less efficient. However, their price per watt is 10% cheaper than Mono-Si solar modules. In order to get the maximum power from solar modules, it is imperative to choose solar modules that feature high quality elements, from reliable manufacturers, and not focus on the crystalline type. Although, in theory, Mono-Si units have more stable characteristics and higher efficiency (Muhammad *et al*. 2019, Marius 2016).

4. FACTORS AFFECTING THE PERFORMANCE OF PV MODULES

4.1 Solar Radiation Spectrum

How much primary solar energy is available for the construction of the solar power station depends on a number of factors, including the geographic coordinates of the station's location, the total solar radiation intensity at the solar system's installation site, the earth's surface's reflectivity, and the amount of cloud cover. It practically excludes the possibility of reliable determination of meteorological factors by theoretical methods. Because most meteorological factors are random in nature, and their components contain fluctuations from at least milliseconds to several decades over time, so at present, probabilistic (statistical) methods are often used to calculate radiation characteristics, which use special climate reference books or databases. Electronic data compiled based on the results of long-term meteorological observations as primary data (Alkholidi *et al*. 2019, Kamilia 2022).

Solar radiation it is a measure of the amount of strength or intensity of sunlight falling on a specific surface and is measured in watts per square meter. It is possible to predict the average monthly and yearly energy production of a system using standardized historical weather data because weather conditions are more or less the same over the years. There are maps available showing the amount of solar radiation reaching the surface of the modules. Standard maps provide data showing the number of standard hours of sunshine, which can be calculated over the course of a month or a year (Plants 2015).

Below is the definition of each component of the radiation that reaches the solar module:

- Direct radiation: solar radiation that is not dispersed in the atmosphere. It hits the surface of the solar module directly.
- Diffuse radiation: solar radiation that has changed its direction due to particulates and atmospheric gases. He crashes into a roof of the Celestial Vault.

- Reflected Radiation: Solar radiation that hits the Ground (or any other solid body on the Earth's surface) and then hits the surface of the solar module (Domínguez-Álvarez *et al*. 2021, Plants 2015).

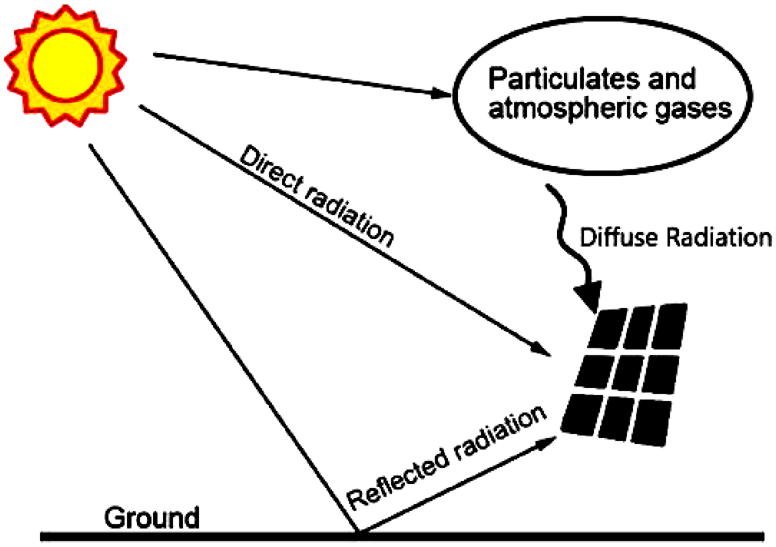


Figure 4.1 Basic Components of solar irradiance: direct, diffuse and reflected radiation (Domínguez-Álvarez *et al*. 2021).

4.2 Solar Insolation

Solar insolation is a measure of the solar radiation reaching the surface of a PV module at any time. The available solar energy at a given location is expressed as kWh/m2/day. This is commonly referred to as peak sun hours (PSH).

Intense sunlight leads to higher output of PV modules. Decreased levels of sunlight result in lower instantaneous output. Variations in the intensity of sunlight do not change the voltage appreciably (Alkholidi *et al*. 2019).

The map below shows the amount of solar energy, in hours, available each day on an optimally inclined roof during the worst months of the year for electricity generation (based on solar insolation data accumulated worldwide). These estimates are commonly used in the PV module design process and are measured in kilowatt-hours per square meter per day (kWh/m2/day). This is very useful because it allows calculating the energy generation of any solar system (Suri and Cebecauer 2014).

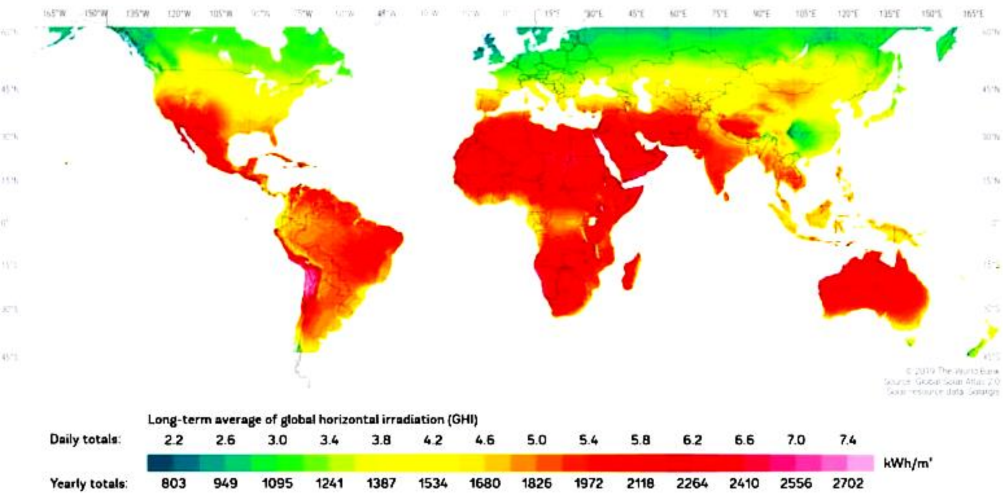


Figure 4.2 Statistical estimates of average daily insolation levels for specific locations (Gasca 2013).

To generate electricity during the available sun hours of the day, there are several factors that affect the amount of solar energy that the PV modules will be exposed to:

- When will the system be used - summer, winter or all year around.
- Typical local weather conditions.
- Using fixed stands to install modules or using tracking devices.
- Location and angle of the PV array.

4.3 The Air Mass Effect

The (AM) is the level at which the atmosphere reduces the light reaching the Earth's surface. The clarity and thickness of the air through which sunlight passes to reach the modules refer to the AM (the angle of the sun has an effect on this value). The standard for this value is 1.5.

4.4 Sun Angle and PV Orientation

The photovoltaic (PV) output of a solar array is inversely proportional to the amount of sunlight falling on it, hence appropriate array orientation is essential. The solar module's orientation with regard to the sun is indicated by the tilt angle, which is calculated from the base of the module to the horizon. The amount of sunlight that strikes the array fluctuates throughout the day because of how the sun moves across the sky.

Solar panels may capture the most radiation when they are positioned correctly. A PV module needs the sun's rays to be perpendicular to the panel in order to work at maximum efficiency. Yet, when the sun's rays are increasingly reflected, the PV modules will reflect rather than absorb increasing amounts of solar energy.

PV systems must be installed permanently, unlike portable solar panels. Trackers that travel from east to west throughout the day may provide more energy if solar panels are installed on them. Nevertheless, because to its high cost, this technique is not often employed in PV systems.

4.5 Effect of Shadow and Dust on PV Modules

One of the most important criteria for energy loss in a PV array may be shading or dust. Even partial shading of a single cell of a solar module can reduce power output significantly.

Possible shading sources can be trees, shrubs, neighboring buildings, and self-shading by multiple rows of the same modules. To avoid winter shading in the middle of the day, calculations must be made to find the minimum distance between rows of PV array (Dambhare *et al.* 2021).

4.6 Solar Cell

A clean and silent energy source, the photovoltaic (PV) cell directly converts solar radiation into electricity without the need of any moving parts by employing the photoelectric effect. At its terminal, a photodiode produces a DC current. A PV solar cell's maximum power output, or IMAX or IMP, depends on many factors, including the amount of direct sunlight impacting the cell, how well the cell converts solar energy into current, and the size and surface area of the cell. Simply put, a silicon solar cell is a p-n junction device that has been configured such that the n-side is exposed to light. The structure of a Si photocell is shown in Figure 4.3 below, where the n-type denotes the negatively charged electrons supplied by the donor impurity atoms and the p-type denotes the positively charged holes created by the acceptor impurity atoms (Suri and Cebecauer 2014).

An unbalanced zone between p-type and n-type semiconductors is the depletion area, sometimes referred to as the space charge region. The n-type is physically thinner than the p-type in order to allow for quicker electron movement and current production prior to recombination with holes. In order to increase light transmission to the semiconductor material and reduce surface reflection, an anti-reflective coating is also applied to the n-layer. The electrons and holes move to their respective ground states—the n-type negative neutral zone and the p-type positive wafer when a photon from the sun with sufficient energy enters the system. A typical 100 cm2 PV cell produces 1.5 watts of electricity (0.5V and 3A per second) (Camellia 2022).

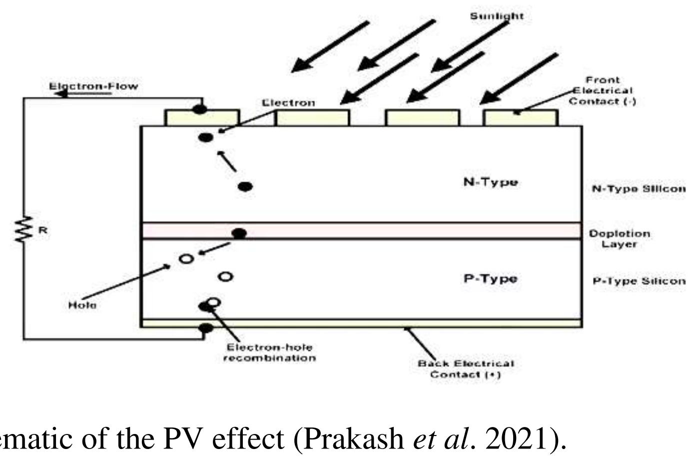


Figure 4.3 Schematic of the PV effect (Prakash *et al*. 2021).

The quantity of carriers produced, which is related to the semiconductor's absorption capabilities and how well it transforms absorbed photons into charge carriers, determines the current. The intrinsic electric field of the diode has a direct relationship to the voltage's strength. Photovoltaic cells lose efficiency over time. Climate, humidity, air pollution, sunshine, and other factors might all expedite the degeneration. A solar cell's rate of degradation over time is dependent on the materials used to build the cell.

4.7 Solar Cell Equivalent Circuit

One or more PV arrays are used by a PV grid to convert solar energy into useful electricity. A PV cell is the main part of a PV array, which is built on the PV effect. The external electrons in a photon may break the link and convert light into electrical energy if its energy exceeds the bandgap energy of a semiconductor. As the PV cell converts light into energy via this process, the PV effect is essential to understanding how solar cells operate. The most crucial indicators of a solar cell's performance are current and voltage, and the relationship between these two parameters may be understood using a equivalent electric circuit (Sera *et al.* 2007).

The p-n junction, the light-induced current source Iph, the leakage current, the parallel resistor (Rp), and the series resistance (Rs), all features of the solar cell and its components, may all be substituted by a diode. This identical phenomena is seen in Figure 4.4.

Although the equivalent circuit of a perfect solar cell can be expressed by simply connecting a current source in parallel with the diode, in practice no solar cell is perfect, so the model must be enhanced with a parallel resistance and a series resistance to account for the different loss mechanisms that occur in solar cells. (Park *et al*. 2016, Sera *et al*. 2007).

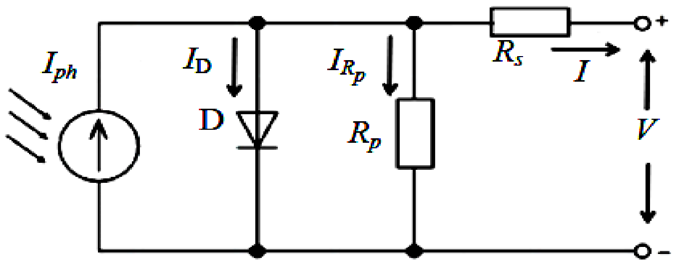


Figure 4.4 PV cell equivalent circuit (Park *et al*. 2016).

As demonstrated in the circuit, solar cell output current equals current source output minus current through diode minus current via parallel resistor as shown in Equation (4.1), (4.2).

$$I = I_{ph} - I_D - I_{Rp} = I_{ph} - I_{sat}[exp(\frac{V+IR_S}{V_T}) - 1] - \frac{(V+IR_S)}{R_p} \tag{4.1}$$

Where, I_{ph} photo-generated current, I_{sat} The dark saturation current in the diode, R_s is the equivalent series resistance, R_p is the equivalent parallel resistance, V is the output voltage, I output current, V_T is the junction thermal voltage,

$$V_T = \frac{kT}{q} \tag{4.2}$$

Where q Electron charge (1.6×10^{-19} C), k Boltzmann's constant = (1.38×10^{-23} J/K), T is the cell temperature in Kelvin.

In short circuit conditions the generated current is the maximum (Isc), while with the open circuit the voltage is the maximum (Voc). In these two situations the electrical energy produced in the cell is zero, while in any other situation, when the voltage increases the energy produced also increases: at first it reaches the MPP then fall to a value close to the voltage value without load (Villalva *et al*. 2009).

The temperature coefficient of almost all Mono-Si solar cells falls within the range (-0.3%/C to -0.5%/C). Hence, the efficiency of a Mono-Si solar cell momentarily drops by 0.3% to 0.5% when the temperature of the solar modules is elevated above 25°C (standard test temperature) by 1°C (32°F) (Cubas *et al*.2014).

4.8 Characteristics of I-V Curves for PV Cell/Module

Critical properties provided by the I-V curve may be utilized to assess the PV module's quality. The I-V curve of the PV cell or module shows the different current and voltage outputs that may be anticipated from it. An I-V curve may be used to display the current and voltage output by the PV cell or module at any given moment (Adeeb *et al*. 2019).

The PV cell or module produces its maximum current when there is no resistance in the circuit. That is, when there is a short circuit between the negative and positive terminals of the PV cell/module. This kind of current is known as "short circuit current" (Isc). When there is a short circuit, there is no voltage (Dambhare *et al*. 2021).

The open circuit voltage (Voc), which happens when the circuit is open, is the greatest voltage that can be accessed from a PV cell or module. In this case, there is no current because the circuit is incomplete, and the resistance between the two ends of the PV cell/module is infinite (Hernandez 2015).

Maximum Power Point (MPP) or Pmax is the operating point at which maximum power is gathered from a PV module. It is the peak of the illuminated I-V curve. Where the product of current (Imp) and voltage (Vmp) is the maximum. As the open circuit voltage (Voc) and short circuit current (Isc) are used to compute the maximum power of the PV module (PT), FF serves as a primary indicator of the PV cell's or module's quality (Cubas *et al* .2014, Shishkin *et al.* 2019). PV module output and the I-V curve are strongly influenced by variations in solar radiation levels and operating cell temperatures, which are graphically depicted as the ratio of the rectangle sections in Figure 4.5. (Mestre 2011).

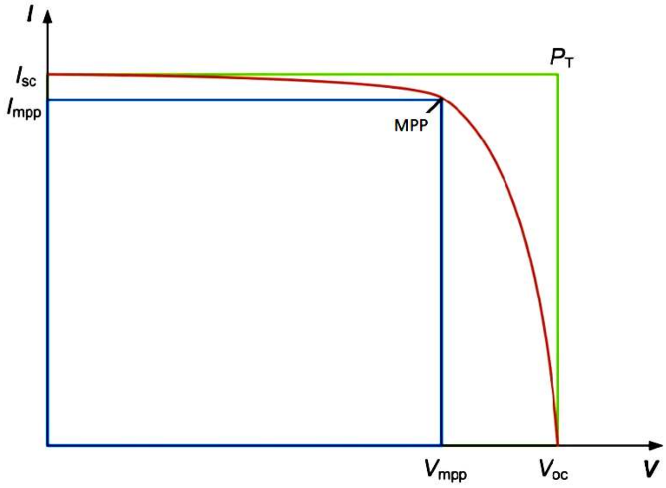


Figure 4.5 I-V characteristics of a solar cell/module in light (Prais 2020).

1) Radioactive effect

The productivity of the PV cell/module depends directly on the amount of solar radiation falling on its surface. The higher the amount of solar radiation, the higher the value of the electric current coming out of the PV cell/module, due to the increase in the level of the PV effect. On the other hand, the voltage changes slightly with the change in irradiance, and this means that as soon as the solar radiation falls on the PV modules in the morning, the voltage rises to a value close to the open circuit voltage Voc. Regardless of the change in the solar radiation, the voltage value will change slightly. Therefore, the passage of a cloud over the project will not significantly affect the voltage value (Adeeb et al. 2019).

As for the electric current, it increases directly with the increase in the amount of solar radiation with constant internal resistance, as the value of the current reaches the value specified in the technical specifications of the PV modules when the amount of solar radiation reaches 1000 watts /m2, and for this reason, the value of the electric current will decrease directly and significantly when a cloud passes from above the project. As the shadows have a direct impact on the energy produced (Maoulida 2020, Prais 2020).

Solar module capacity and performance curve are affected by temperature and radiation change. Where radiative changes result in a direct linear change in current and a small direct change in voltage (Adeeb et al. 2019).

The Figure below shows the difference in the power output of the PV module with the amount of light falling on it varying at a constant temperature.

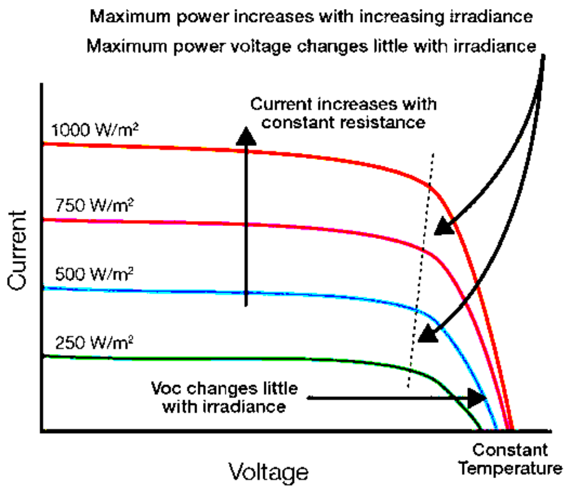


Figure 4.6 Radiation effect on I-V curve of PV cell (Rodrigues *et al*. 2011).

2) Influence of temperature

The performance of PV cells/modules and the energy produced from them changes directly with temperature, because PV cells cannot convert all solar radiation falling on them into electrical energy. Where part of the incident solar radiation is transformed into heat losses, which leads to a rise in the temperature of the PV cells (Jailany *et al*. 2016, Hernandez 2015).

As the temperature of PV cells rises, the power produced by the modules decreases, as the open circuit voltage Voc drops dramatically when the temperature of the cells rises. The short circuit current (Isc) rises slightly as the temperature rises, but not enough to compensate for the large drop in voltage Voc (Adeeb *et al*. 2019).

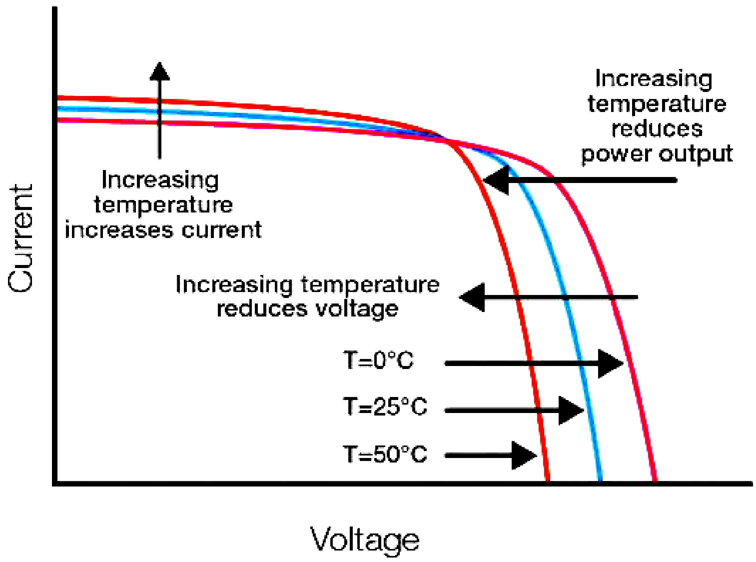


Figure 4.7 Effect of temperature on the I-V curve of PV cell (Hernandez 2015).

5. SOLAR CELL PARAMETERS

5.1 Important Solar Cell Parameters

For solar cells, the I-V measurement is invaluable because of the clarity with which it delivers information on device performance while being one of the simplest electrical characterization techniques available. The image below demonstrates the standard I-V characteristics of a solar cell in both its dark (black curve) and light state (red curve). The photocurrent in the illuminated solar cell flows in the opposite direction, so it is usually represented as negative. Thus, the I-V characteristic of the solar cell under illumination deviates downward by the value of Isc, as shown in Figure 5.1. Several crucial aspects may be inferred from I-V characteristics when illuminated. I-V measurement made with the lit solar cell may be used to derive the short circuit current Isc, open circuit voltage Voc, FF, and efficiency.

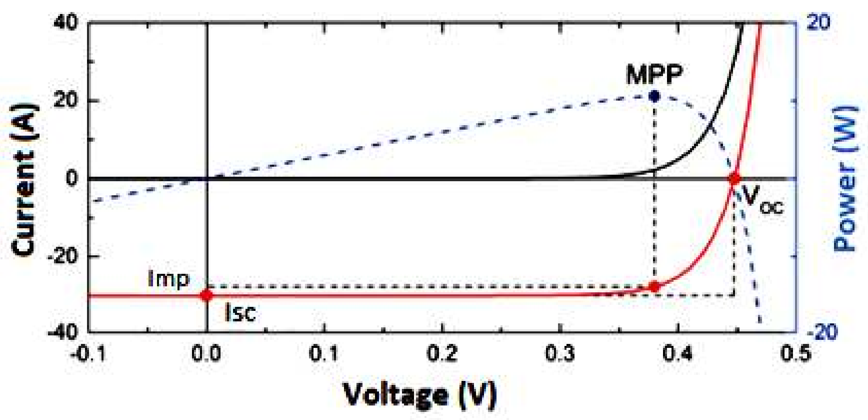


Figure 5.1 I-V characteristics of a P-N junction in the dark and under illumination (Jean *et al* 2015).

5.2 Short-Circuit Current (Isc)

When the electrodes of a solar cell are connected, the load resistance is zero and an electrical current flows via the external circuit. The greatest current achievable is referred to as "short circuit current" (Isc). This amount exceeds the maximum working circuit current, which is denoted by (IMAX) or (Imp). The circuit in this instance is devoid of both voltage and resistance. (Zeman 2003, Amu 2014).

Isc or short circuit current, is sensitive to the kind of light and amount of photons that enter the circuit. In an AM1.5 spectrum, C-Si solar cells may produce up to 46 mA/cm2. (Green1982).

5.3 Open-Circuit Voltage (Voc)

It is the highest voltage that the solar cell can generate when the current flowing through the cell is zero under STC conditions, given that there is no load connected to both ends of the module, and therefore no current is produced. It is a function of the semiconductor bandgap and charge recombination in the cell. Voc depends on the energy barrier, decreases with temperature, and changes slightly with light intensity. Provided there is no current flow and and the resistance is unlimited. Voc is given through the relationship:

$$V_{oc} = \frac{kT}{q} \ln(\frac{I_{ph}}{I_{sat}} + 1) \quad (5.1)$$

Where $\frac{kT}{q}$, is the equivalent thermal potential, and its value is 0.026 V at STC temperature, I_{ph}, I_{sat} is the photocurrent generated by the PV cell and reverse saturation current, respectively. Equation 5.2 shows that Voc depends on the saturation current of the solar cell (Isat) and the current generated by the PV cell (Iph). Reducing Isat is crucial for improving overall solar cell performance. That commercial solar cells usually have a Voc slightly above 600mV while a solar-facing C-Si cell in a research facility has a voltage of about 720mV under STC conditions (Nassiri Nazif *et al.* 2021, Aribisala 2013).

5.4 Series and Parallel Resistance

The internal resistance of the PV modules dissipates the PV energy during normal operation, decreasing the efficiency of the cells. To imitate this parasitic resistance, series resistance (Rs) and parallel resistance (Rp) may both be employed (Rp). As there is no parallel resistance Rp to redirect the current and its value is infinite, but the value of the series resistance Rs is zero, there is no power loss before reaching the load, and there is no voltage drop. By raising the series resistance Rs and lowering the parallel resistance Rp, the MPP and FF may both be decreased (Köntges et al., 2014). I-V slopes at Voc and Isc may be used to approximately compute the Rs and Rp. Resistance at Voc is more than and, at most, proportional to series resistance. In ISc, the parallel resistance Rp is represented by the slope. A decent estimate of the series resistance Rs and the parallel resistance Rp may be obtained by eliminating the slope of the light I-V curve at the locations where I = 0 and V = 0. Have a look at Figure 5.2 for more information. In a perfect world, the series resistance would be kept to a minimum while the shunt resistance would be kept as high as practical.

The series resistance Rs in solar cells is influenced by contact resistance, metal grids, and charge transfer resistance in the semiconductor material (p and n layers). Series resistance affects maximum power output whereas extremely high levels of series resistance Rs reduce short-circuit current. The open-circuit voltage remains constant while the whole current travels through the cell and into the series resistance (Cuervo 2012).

Solar cells display a parallel resistance, represented by the symbol Rp, as a result of leakage current via the p-n junction. The parallel resistance Rp varies in direct proportion to the level of manufacturing, the presence of structural faults, and the condition of the surface. Due to the lowered parallel impedance, which provides an extra current channel for the current generated by the PV cell, significant power losses are experienced. A decrease in either one may be anticipated to decrease the maximum power output since the parallel resistance and the open circuit voltage are both proportional to one other. This number is insignificant because only a very small portion of the short circuit current Isc really travels through the parallel resistance and, therefore, the external channel. While similar resistance is often rather high, manufacturing flaws might cause it to be low (Garcia 2019). The effect of parallel resistances will be more noticeable at lower light levels since the voltage does not fluctuate significantly with radiation. Moreover, when there is a little photocurrent, the current across the parallel resistors will be greater than the sum of their individual values (Cuervo 2012).

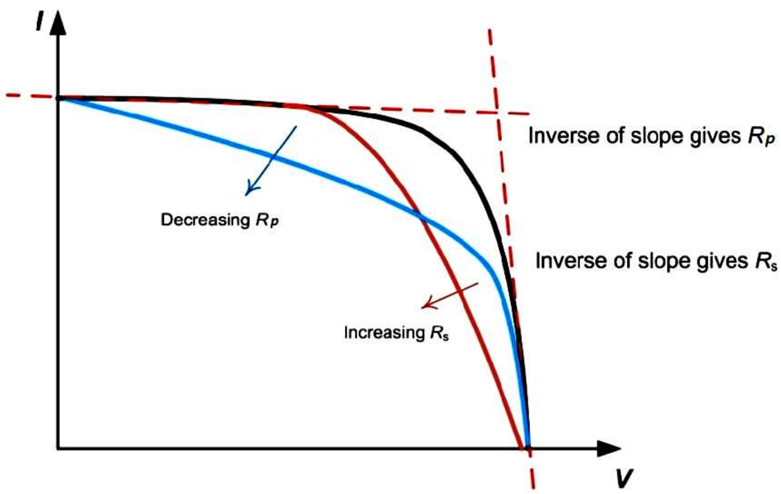


Figure 5.2 Effect of changing series resistance Rs and parallel resistance Rp from ideality (Köntges *et al.* 2014).

5.5 Fill Factor (FF)

The FF is one of the indicators of the quality of PV cells. It reflects the value of the Series Resistance and Shunt Resistance present in the cells.

The FF is calculated by dividing the maximum operating power (MPP Tracking) by the virtual power point (P_T) (which cannot be achieved), which is equal to the open circuit voltage (Voc) multiplied by the short circuit current Isc (Aribisala 2013). This value is always less than 1, and the higher the value of the FF, the higher the quality of the cell. A value greater than 0.7 is typical for high-quality cells. As shown in the equation below:

$$FF = \frac{P_{max}}{P_T} = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}} < 1 \qquad (5.2)$$

Where V_{mp} and I_{mp} are the voltage and current at the point of maximum power.

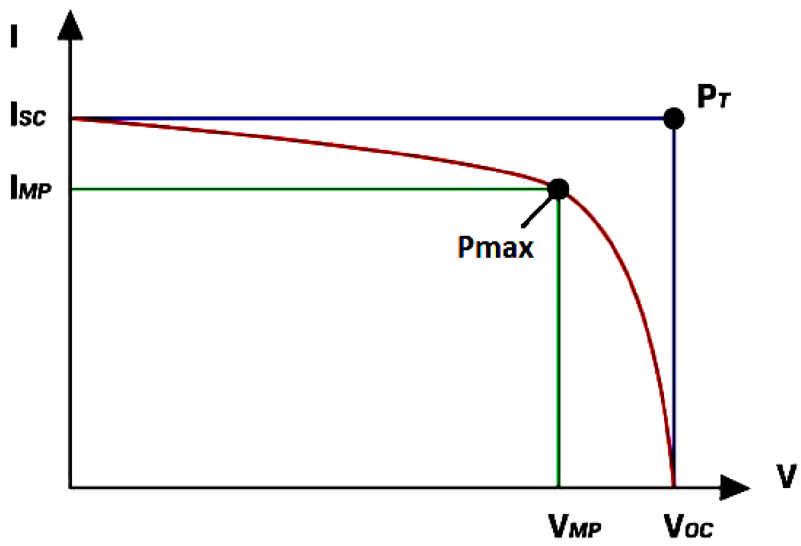


Figure 5.3 Calculation FF through I-V curve (Cotal *et al*. 2009).

The FF has no modules of measure because it is a ratio between the same physical parameters. Obviously, FF will always be a value smaller than one and the better the solar cell the closer the FF value will be to this number. But this is virtually impossible because of the serial resistance losses and parallel resistance losses (Cotal *et al*. 2009).

Cells made of Mono-Si, have a better FF value than those made of Poly-Si. The FF gives an idea of the quality of the PV array. The closer the FF is to 1, the more power the solar array can provide. FF values range from 0.75 to 0.85 for C-Si cells and from 0.55 to 0.75 for thin-film cells. During the commercial solar module manufacturing process, each solar module is tested for its FF. Solar modules are considered second order if the FF is less than 0.7 and are therefore excluded (Nassiri Nazif *et al*. 2021, Amu 2014).

5.6 Conversion Efficiency

A PV module efficiency is the ratio of solar radiation falling on the PV module that is converted into electricity relative to total radiation falling on the same module. The conversion efficiency is calculated as the ratio between the maximal generated power and the light incident power. The efficiency of the PV module is always less than the efficiency of a single cell, due to the presence of voids between the cells that make up the

PV module, in addition to calculating the unit frame area from the total unit area in calculating the efficiency. Typical Si efficiency values usually do not exceed 20% except for high-quality modules.

From the output parameters (Voc, Isc, FF), it is possible to determine the energy conversion efficiency of the cell. It is the most important parameter because it allows the performance of the PV cell to be assessed (Zeman 2003).

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{mp}V_{mp}}{P_{in}} = \frac{I_{sc}V_{oc}FF}{P_{in}} \tag{5.3}$$

Where, V_{mp} and I_{mp} are the voltage and current at the point of maximum power, P_{in} is the total incident light power of the device, and is equal to 1000 W/m^2 for AM1.5 spectrum, which has become a benchmark for measuring the conversion efficiency of solar cells. The greatest potential efficiency for a Si-based solar cell is about 30%, with the highest efficiency being 25.6%. (Gallegos and Alvarado 2015).

Energy conversion efficiency (η) is crucial because it defines how efficiently a solar cell can utilise its space and how much surface area it has to cover to generate a certain quantity of electricity. A higher is often desired since covering greater regions with solar cells necessitates more resources. By raising Voc, the open circuit voltage, and Isc, the short circuit current, we may make it better. The spectrum and intensity of falling light, as well as the temperature of the solar cells while they are operating, all affect solar cell performance (Khan 2013, Hernandez 2015).

5.7 Maximum Power Point (MPP or Pmax)

Maximum power is the point on the I-V curve which, under any environmental conditions, the PV generator always delivers maximum energy. So, it is better to work in MPP (Femia *et al*. 2005). This relates to the point at which the energy provided by the matrix is connected to the load (inverters, Batteries) are at their maximum value, where:

$$P_{max} = I_{mp} V_{mp} \tag{5.4}$$

Where V_{mp} and I_{mp} are the voltage and current respectively at the point of maximum power.

Nevertheless, the PV array's nominal voltage and current will not always be available since solar irradiance varies over time. Figure 5.4 displays the I-V curves for a PV module under different operating situations. The maximum power point tracking (MPPT) guarantees that the PV modules are always drawing their maximum amount of electricity. A number of algorithms may be used to accomplish MPPT control, and some of them can even increase a PV array's output by more than 98%. This technique progressively modifies the supply current while monitoring the power output to get the ideal voltage setting (Esram and Chapman 2007).

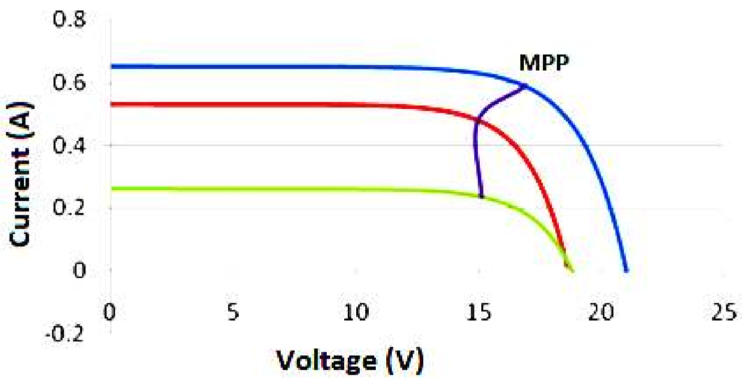


Figure 5.4 I-V Curves for a PV Module at different operating conditions (Esram and Chapman 2007).

However, in order to control this action point, it is necessary to impose voltage on the PV module using electronic transformers so that they are present in the desired area. The specificity of the I-V curve allows PV module, with the help of the adapter, to repair practically any action point. To modify the working voltage, it is necessary to implement a controller that places the module in MPP in real time using current and voltage gauges of the PV generator. These controllers are called MPP Trackers (MPPT) and operate on the electronic converter's running time to regulate its voltage (Benito 2020, Femia *et al*. 2005).

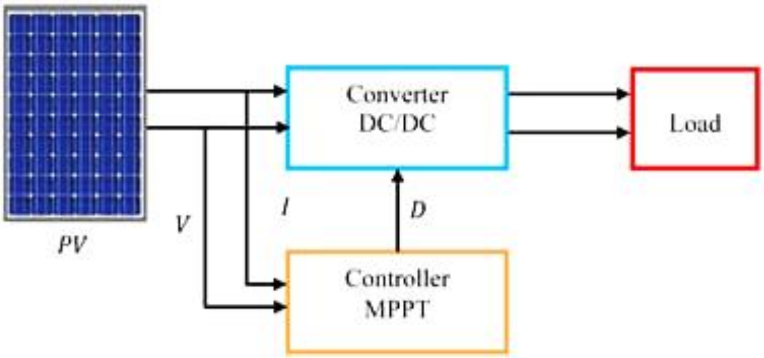


Figure 5.5 MPP Monitoring System (Benito 2020).

6 PV SYSTEM CONFIGURATIONS

6.1 Introduction

After discussing the initial logical assumptions required for solar modules, the information obtained should be used to study all components of the PV system. A PV system has many distinct components, it is essential to understand all of these components and know their key capabilities and characteristics for the effective installation of a PV system.

Because the size of a solar cell is somewhat limited, it can only supply a limited amount of power under a certain voltage, making it impractical in many applications. So, an array of solar cells must be integrated if you want to consume a lot of power (high voltages or currents). Solar cell modules are the main component of a PV system. However, it also needs many other devices to work. All components of the system except PV modules are called (BOS). The basic parts and components that make up a BOS are:

1) Solar module mounting systems: It is used to install all modules and orient the cells in the direction of the sun.
2) Charge regulator: In stand-alone PV systems and some hybrid systems, the batteries are connected to the PV array via a charge controller. Charge controller protects batteries from overcharging or deep discharging. It can also enable metering and payment for electricity used or provide information about system status.
3) Energy storage unit: Batteries are usually used as energy storage devices. They are a critical component of off-grid systems because they ensure that the BOS can provide power at night and during periods of cloudy or overcast weather (Copetti and Macagnan 2007).
4) DC-DC converters: used to convert the output of modules into a constant voltage output, because the modules will have a variable voltage depending on the day time and weather conditions. In network connected system can be used as inverter input or for battery charging.

5) Inverters: They are also called DC-AC converters. These inverters are used to convert DC voltages/currents from PV modules into AC signals for specific power devices.

In addition to PV modules, charging regulator, batteries and inverters, there are other solar components required in the PV grid system. The most common components are cables, power enhancers, electricity meters, assembly boxes, keys, protection devices, transformers, etc. The various parts and components of a PV system are shown in Figure 6.1.

Figure 6.1 PV system components.

6.2 Types of PV Systems

The photovoltaic (PV) modules are only one of many individual parts that together form the solar power system. You can't effectively design a solar photovoltaic system without first having a firm grasp on how the key components operate and what their major duties are. It is also important to understand how modest industrial interests, residential loads, or single direct loads could affect the (expected) performance of the PV module installation location. Understanding the different components of the solar system and how they interact can help you make a sound financial decision.

A direct PV system consists of merely a PV module and a load, such a water pump with a direct drive motor that only has to run while the sun is shining. Yet, when a house is fully occupied, the system must operate around the clock. It can power AC as well as DC loads.

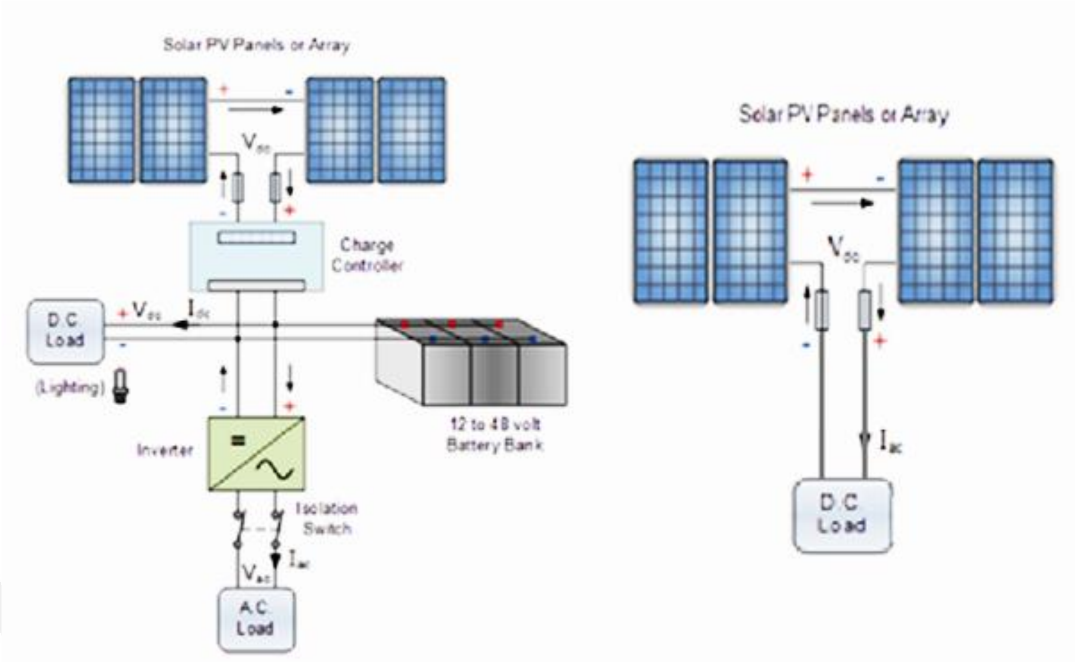
There are three primary kinds of PV systems, each distinguished by a different approach to system design. Different types include standalone, grid-connected, and hybrid designs.

The principles and main elements of a PV system are generally the same. To meet some special requirements, this PV system is modified by changing the quantity and quality of its components.

6.2.1 Standalone solar PV Systems

Solar energy is the sole source of power for autonomous systems. For such systems, all that is required are either PV modules and the load or PV modules plus batteries for energy storage. Charge regulators are a common component of battery systems that, when the batteries are full, stop electricity to the PV modules and, in certain circumstances, reduce power to the load to prevent the batteries from being overdrained.

In order to utilize the energy produced during the day at night or adverse weather, it must first be stored in batteries. A Simple DC Solar Power System without a battery and a Freestanding Solar Power System that can handle both direct current and alternating current needs are two examples of freestanding systems that are often used.Standalone PV systems are ideal for isolated buildings where it would be too expensive to connect power lines, or to bring electricity to areas that do not have local electricity services such as remote rural areas or some offshore islands, in these cases installing a standalone PV system is more effective than in terms of cost. Instead of paying the local electric company to lay their cables and power lines directly to the area (Abella 2005).



(a) (b)

Figure 6.2 (a) solar standalone system including batteries, (b) Standalone PV system without battery (Alternative Energy Tutorials, 2017).

6.2.2 Grid-connected PV solar systems

There has been a recent uptick in the use of solar power systems that are connected to the grid for use in integrated building applications. The inverters, which convert DC power to AC energy, are used to link the solar power system to the grid, as depicted in the Figure below.

PV systems connected to the national grid are of two types:

- The grid-connected PV system without a battery or back-up generator is the most popular.

- The grid-connected PV system with a backup battery (some sources consider it as part of the hybrid system).

PV energy may be supplied to the electrical grid or to AC appliances in small systems, such as residential homes, by connecting the inverter to the distribution module. When the PV panels are connected to the grid, any extra energy is transferred back to the grid, and the grid also supplies electricity to the house when the PV panels are not generating enough power (Patel 2017).

The Energy Tariff Company provides energy credit based on the production of solar energy to service providers. This process is called "net metering". In this process, energy enters and exits through a single counter. A grid-tied system is the most cost-effective and simplest way to connect a PV system to the local electricity grid. If the local electricity grid is reliable, and energy storage is not a priority, the PV system does not need to include batteries (Abella 2005).

However, one of the drawbacks of this system is that if the power of the local electricity network fails, the PV system will be turned off even if there is solar energy, for the safety of the local electricity network workers.

The main application of grid-tied PV system is in areas well covered by the national electricity grid.

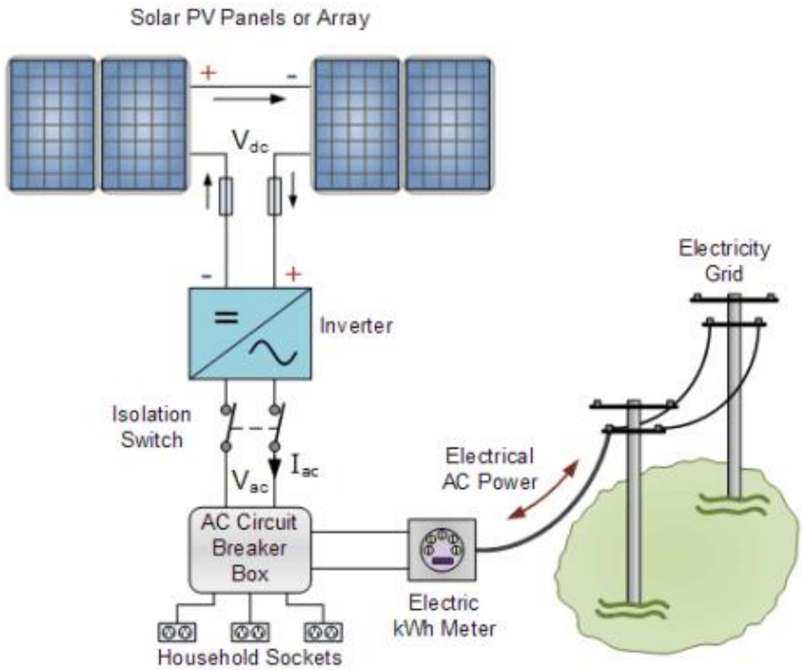


Figure 6.3 Grid-connected PV system schematic (Alternative Energy Tutorials, 2017).

6.2.3 Hybrid solar PV power systems

Hybrid systems may be standalone, relying just on PV modules, or they can be connected to the national electrical grid, allowing their batteries to be charged throughout the night or in cloudy conditions. Only the backup generator may be used to run the load or recharge the batteries. Any extra energy produced by the system may be exported to the grid while the PV system is being used to recharge the batteries.

Hybrid systems require more complex controls than standalone or grid-connected PV systems and do not include batteries. In the case of a grid-connected hybrid system, when the battery reaches a certain discharge level it connects to the local electrical grid, and then disconnects when the battery reaches the appropriate charge level.

A hybrid PV system is ideal in areas that experience power outages due to natural disasters or when living in areas with unreliable power from the electric grid (Patel 2017).

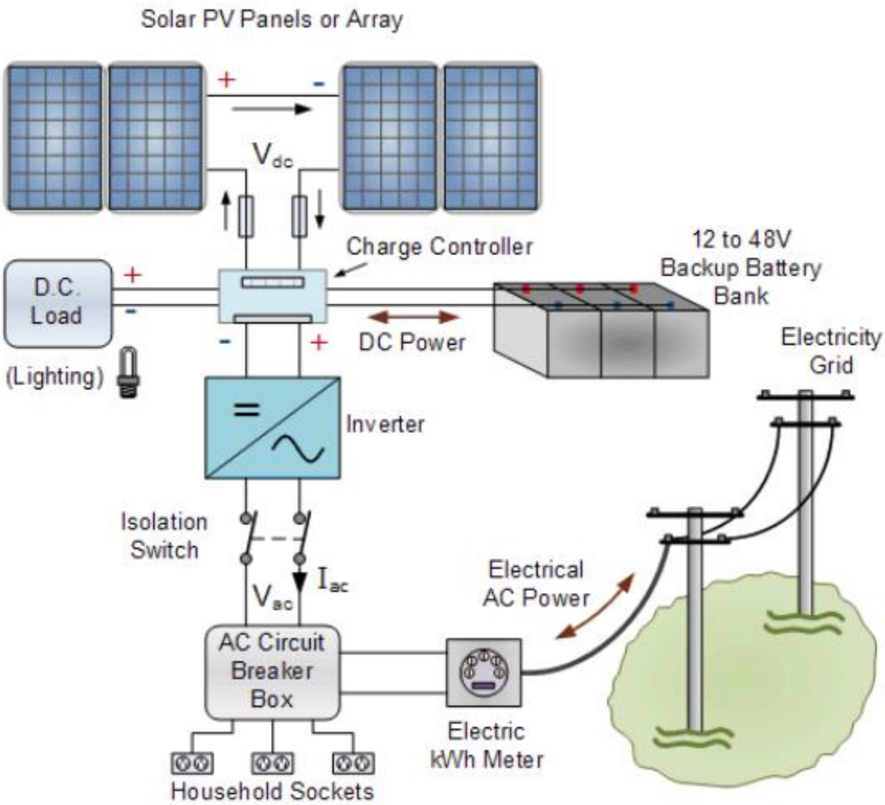


Figure 6.4 A Hybrid PV system connected to the local electricity grid and including batteries (Chico 2017).

6.3 Components of the PV System

6.3.1 PV systems modules

PV cells produce about 0.5 to 0.6 volts DC, where current is directly proportional to the amount of radiation and the surface area of the cell. But what ultimately determines the amount of current supplied by the module or PV cell is the resistance of the connected load. The presence of brighter sunlight increases the output of a solar cell, but no matter how bright and intense the sunlight is, there is a maximum amount of current that a solar cell can generate. So, the cells must be combined to provide enough power for any applications. PV modules are designed to operate at different voltages by connecting solar cells together. Solar modules are linked together in a solar array to generate electricity on a large scale. Cells can be connected in series or in parallel or by combining the two links together.

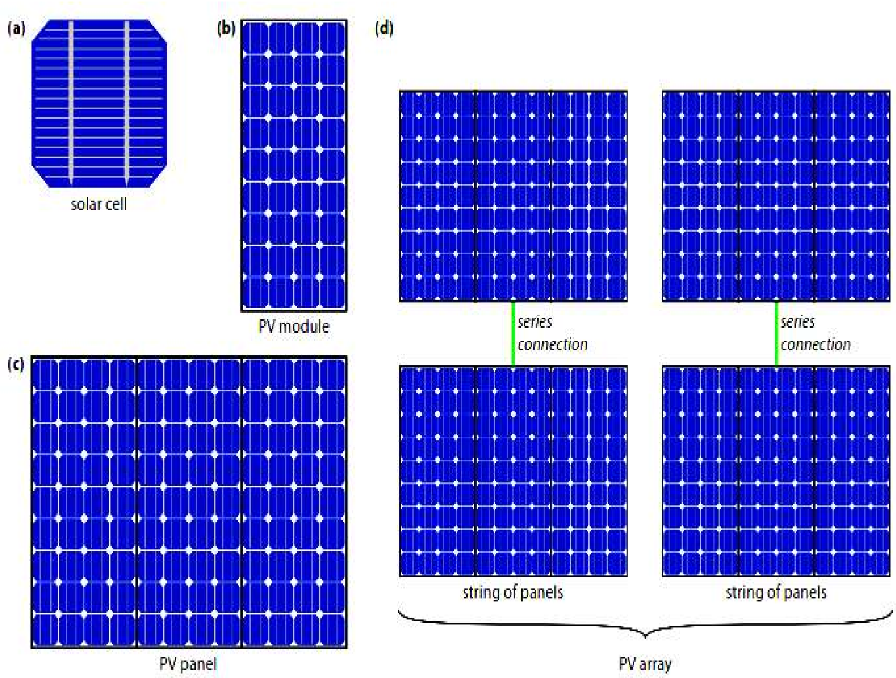


Figure 6.5 (a) solar-cell, (b) PV module, (c) solar-cell panel, and (d) PV matrice (Jäger *et al*. 2016).

- The PV cell, often known as a solar cell, is the fundamental PV device that forms the backbone of all PV modules. Thin-film PV are long and narrow, whereas PV cells are made up of a thin square or round Si wafer. The cells can convert the energy from sunlight into electricity, but they are unable to store the electricity they produce. Solar cells get their energy from sunlight, which is both limitless and widely accessible. Little solar cells can only generate half a volt, whereas full voltage is required to charge batteries or power loads.

- Engineering system made up of several solar cells, a frame, wires, and glass are called a PV module. The smallest package that produces usable energy is made up of a group of PV cells connected in series and/or parallel and covered with environmental protection sheets. To increase power and reduce resistance, solar cells in solar photovoltaic modules are often linked in series. Strict quality assurance and control procedures are necessary for the production of high-quality solar modules. Making your own modules is thus a difficult process. Manufacturers of PV modules have created modules with higher outputs in response to the market need for grid-connected solar systems (termed "big area" modules) (GARCIA 2019).

- A solar panel is set of modules that are the basic building block of a PV array. Solar panels consist of several PV modules that are electrically connected and mounted on a supporting structure. However, these days referring to a PV panel to a single PV module is a bit of a misnomer but common.

- A solar array is a group of solar panels working together as one PV power plant. With 8 panels and 3 modules per panel, a typical matrix has 24 modules. A PV system may include more than one PV matrix.

6.3.2 PV modules connections

As a single solar cell produces little energy, many solar cells must be connected in series to provide adequate power for all purposes. Solar cells may be connected in either a series or parallel arrangement, depending on the application. When two identical cells are connected in series, the voltage doubles but the current remains the same. When two identical cells are linked in parallel, the system voltage is unaltered, but the current is doubled.

Solar modules are often made by wiring many solar cells in series together due to the low voltage that a single solar cell can provide. In general, the more solar cells you need to produce, the more of them you'll need to connect together. Figure 6.6 depicts the functioning of a solar cell array using series connections.

It is obvious that the short circuit current remains constant regardless of how many solar cells are connected in series, rather than changing proportionately with the number of solar cells. The open circuit voltage increases directly as the number of series-connected cells increases. For instance, when two solar cells are connected in series, the Voc and power output are both doubled compared to a single cell. So, it is evident that series wiring between solar cells increases external voltage and, therefore, total power.

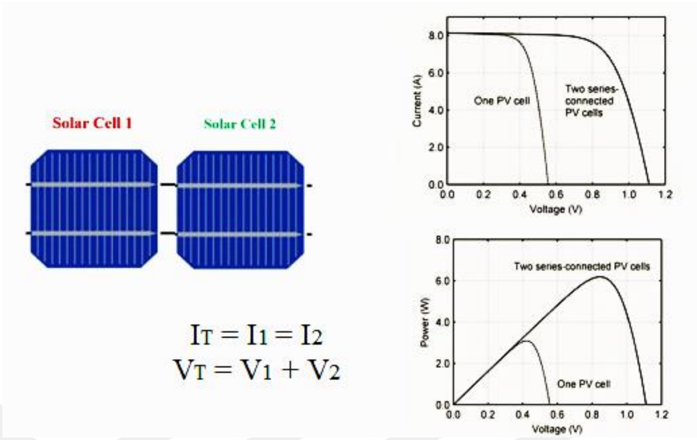


Figure 6.6 Series connected solar cells.

Connecting solar cells in parallel increases the current across the system, as seen in Figure 6.7. As can be seen in the diagram below, the total system current Isc increases when more solar cells are connected in parallel, but the value of V, which is equal to the value of a single solar cell, remains constant. Two solar cells linked in parallel, for instance, provide twice as much electricity as a single solar cell.

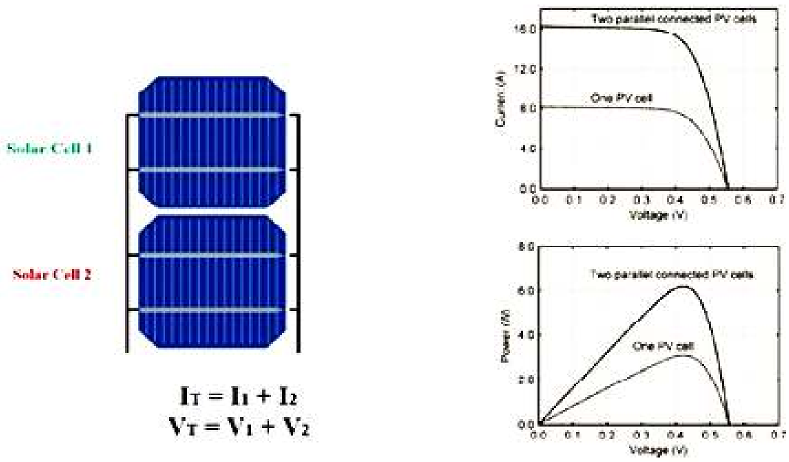


Figure 6.7 Parallel connected solar cells.

A single cell is not able to produce the required amount of capacitance, so a series and parallel array of PV cells is used to increase the output voltage and current of the solar array. The array consists of a combination of parallel and series modules to increase system efficiency and reduce losses. The PV cells/modules are connected in series or parallel groups, or combine connections together to increase the voltage, current, or both and thus increase the output capacity of the solar module or solar system. The MPP generated by the combination of these different PV installations (parallel MPP and series MPP) is not affected but will remain the same, Imp multiplied by Vmp (Kumar *et al.* 2021).

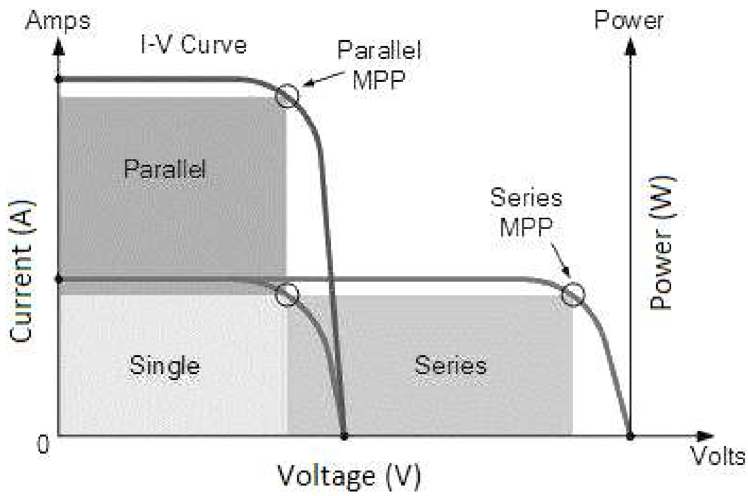


Figure 6.8 I-V curve of series-parallel connected solar cells (Kumar *et al.* 2021).

6.4 PV Module Components

The PV solar module consists of a number of PV solar cells connected to each other electrically and which are encapsulated in one module.

The primary function of solar PV cell packaging is to shield the cells themselves and the electrical connections between them from environmental hazards and weather extremes at the sites where the modules will be deployed. For example, PV solar module, because they are relatively thin, may suffer mechanical damage unless protected. In addition, the wires that hold solar cells together may corrode and rust with exposure to air, water, or water vapor.

The vast majority of commercial PV solar modules consist of a transparent top surface of glass. And then a layer of encapsulation, then a layer of PV solar cells, and then another layer of encapsulation. And finally, a Backet layer in addition to the metal frame.

Below we will review these components with a simple explanation of the role and benefit of each component.

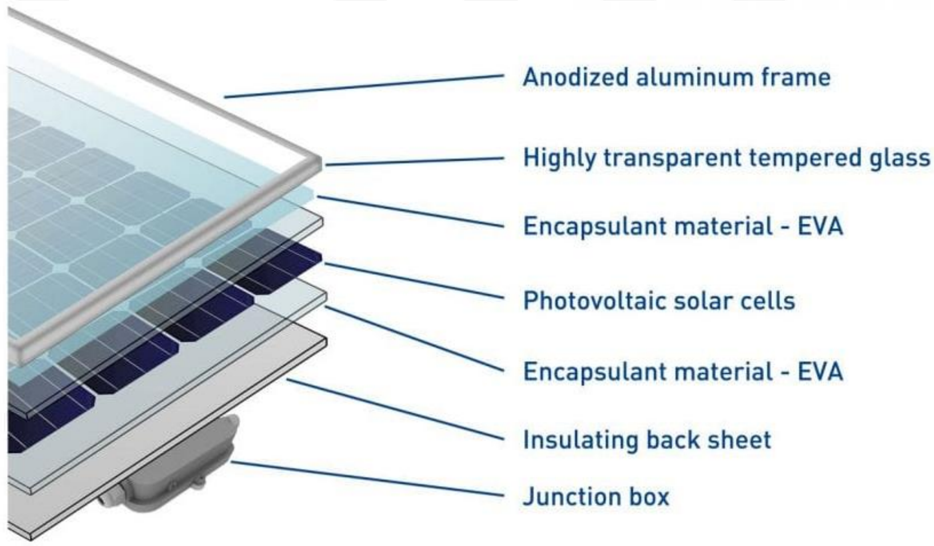


Figure 6.9 Solar PV Module Components (C-Si) (Khan 2013).

• Glass (front surface of PV module): For the passage of positive lengths that may be employed in PV, the materials used as the front surface of solar PV modules has to have high permeability. For Si solar cells the top surface should have high permeability for passing wavelengths in the range of 350nm to 1200nm plus the reflection from the front surface should be low.

In addition to the characteristics of low reflectivity and high permeability, the upper surface material must be impermeable to water and gases. It should have low thermal resistance and be stable when exposed to ultraviolet radiation for long periods. The entry of water or water vapor into the PV module may lead to rust and corrosion of the metal wires connecting between the cells and thus will significantly reduce the expected life of the modules.

The modules' top surfaces may be produced from a wide range of materials, but low-iron toughened glass is a popular choice because to its many desirable properties, including its durability, cost-effectiveness, high transparency, resistance to water and gases, and efficient self-cleaning abilities.

The windshield is the heaviest part of the PV modules. Because it has the function of ensuring the durability and protection of the entire PV modules.

• Packaging materials are used to ensure that the PV solar cells are adhered to the top surface and the back surface of the PV modules. The packaging materials used must be stable under continuous exposure to ultraviolet rays and high temperatures. It should also be transparent, have high permeability and have low thermal resistance.

EVA is the most widely used material as a packaging material in the manufacture of PV modules, and the EVA layer comes as thin sheets that are inserted between the PV solar cells and the upper surface and between the PV solar cells and the lower surface, and then this layer is heated to a temperature Heat up to 150 degrees to polymerize the EVA material and bond the PV module materials together.

• Solar cells (PV cells): PV cells convert the solar radiation falling on them into DC current. These cells are electrically connected together inside the PV modules, and then the final electrical points are connected with the junction box, which is installed on the back of the modules.

• Backsheet: The materials used in the manufacture of the backsheet of the PV modules are characterized by low thermal resistance, as they provide the necessary electrical insulation for the PV modules and prevent the entry of water or water vapor into the PV modules. This layer is made from a variety of polymer materials. Usually, this layer is transparent in bifocal PV modules, while it is white in single-sided PV modules.

• Metal frame: It is usually made of aluminium. The role of the metal frame is to ensure the durability of the PV modules mechanically. There are special applications of PV modules that come with plastic frames instead of metal or come without frame (frameless PV modules).

• Junction Box: Junction boxes in PV modules are responsible for transporting the internal electrical connections to the modules outside. Bypass Diodes are used in the junction boxes to eliminate any damage to PV cells from hot spots.

7. SIMULATION RESULTS

7.1 Simulation

To validate the derived model, the calculated I-V curves are compared with the real value of three commercial PV modules, which are (SR-MFA70W: Mono-Si), (YCPV-70P: Poly-Si), and (SZ-100-36MFE: thin film).

In Matlab, a user graphic interface is designed to compare calculated I-V curve with measured I-V curve for the previous modules.

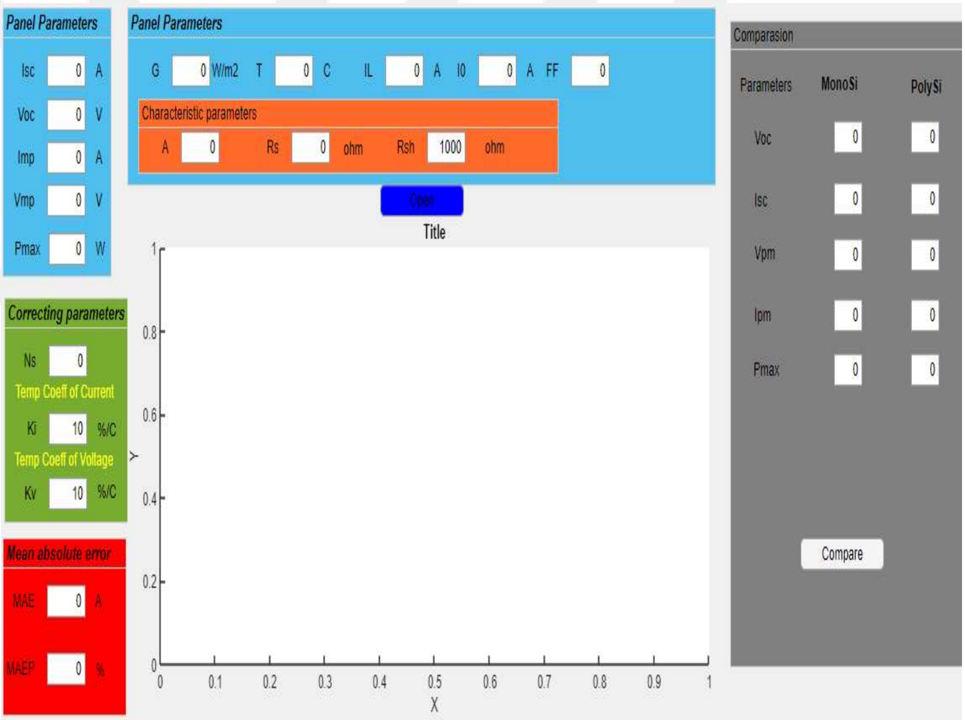


Figure 7.1 Solar panel GUI.

The GUI is showed the module parameters and solar cell parameters, then the I-V curve is drawn, and the mean absolute error is calculated for each type of modules.

For module (SR-MFA70W: Mono-Si) which has the following measured parameters:

Table 7.1 The measured parameters for the module SR-MFA70W

Voc (V)	20.27
Isc (A)	5
Pmax (W)	69.5253
Vmp (V)	15.48
Imp (A)	4.491
EFF (%)	3.576
FF	0.685
Tc (degree)	41.9
Irr (W/m2)	999
Ns	1
Rs (Ohm)	0.685

Using the designed GUI, the I-V curve of calculated value is drawn in red, and I-V curve of measured value is drawn in blue as shown in Figure 7.2.

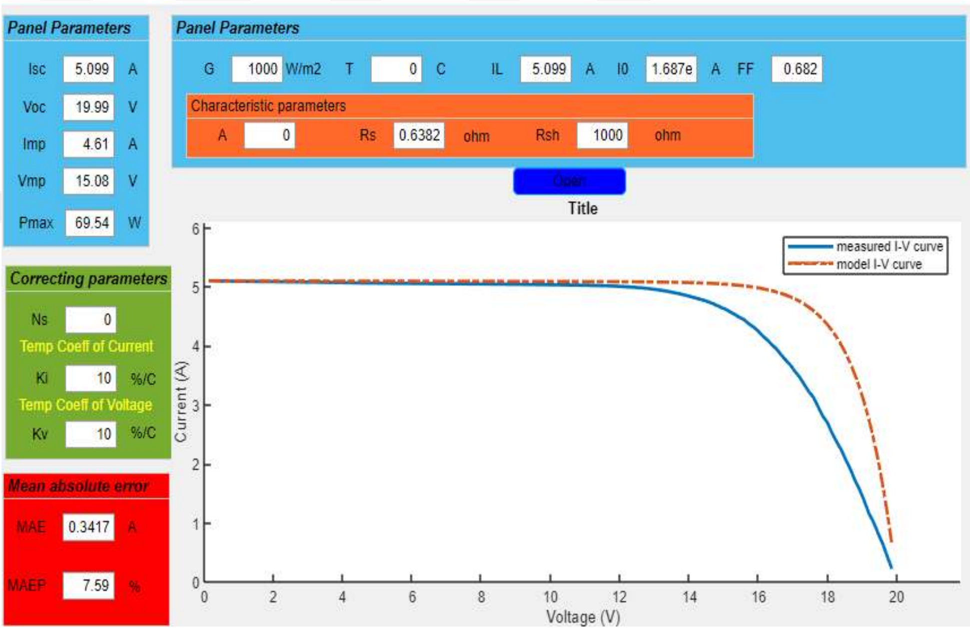


Figure 7.2 (SR-MFA70W: Mono-Si) I-V characteristics.

Using the designed GUI, the I-V curve of calculated value is drawn in red, and I-V curve of measured value is drawn in blue as shown in Figure 7.2.

Table 7.2 Measured parameters for the module YCPV-70P

Voc (V)	20.27
Isc (A)	5
Pmax (W)	69.53
Vmp (V)	15.48
Imp (A)	4.491
EFF (%)	3.576
FF	0.685
Tc (degree)	41.9
Irr (W/m2)	999
Ns	1
Rs (Ohm)	0.678

Using the designed GUI, the I-V curve of calculated value is drawn in red, and I-V curve of measured value is drawn in blue as shown in Figure 7.3.

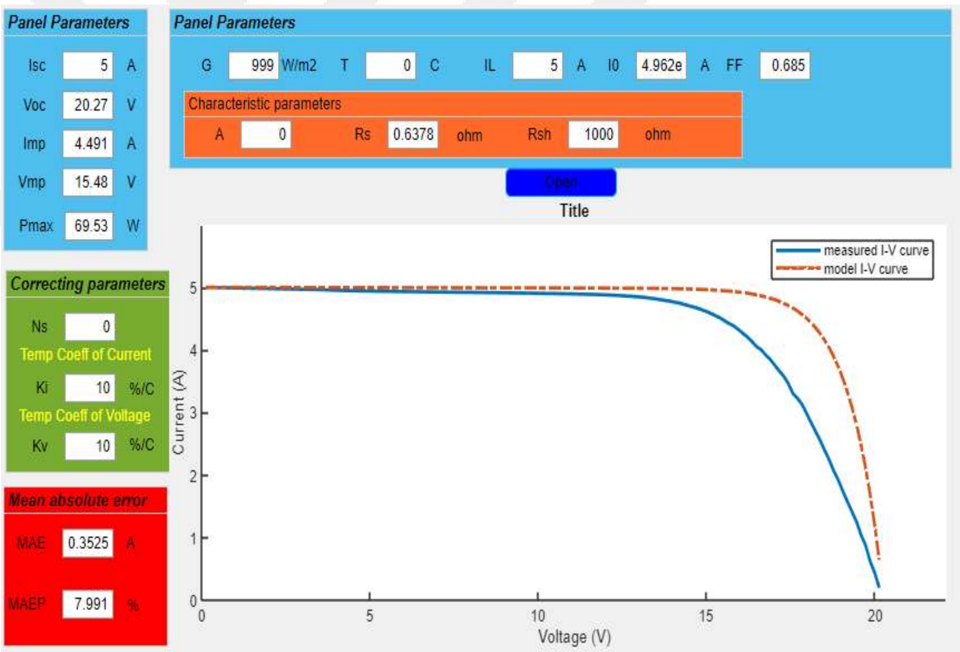


Figure 7.3 (YCPV-70P: Poly-Si) I-V characteristics.

Mean absolute error for current-voltage 0.3525A (7.991%).

For module (SZ-100-36MFE: thin film) which has the following measured parameters:

Table 7.3 The measured parameters for the module SZ-100-36MFE

Voc (V)	42.65
Isc (A)	3.873
Pmax (W)	106.26
Vmp (V)	32.99
Imp (A)	3.22
EFF (%)	5.466
FF	0.643
Tc (degree)	50
Irr (W/m2)	1005
Ns	1
Rs (Ohm)	1.6401

Using the designed GUI, the I-V curve of calculated value is drawn in red, and I-V curve of measured value is drawn in blue as shown in Figure 7.4.

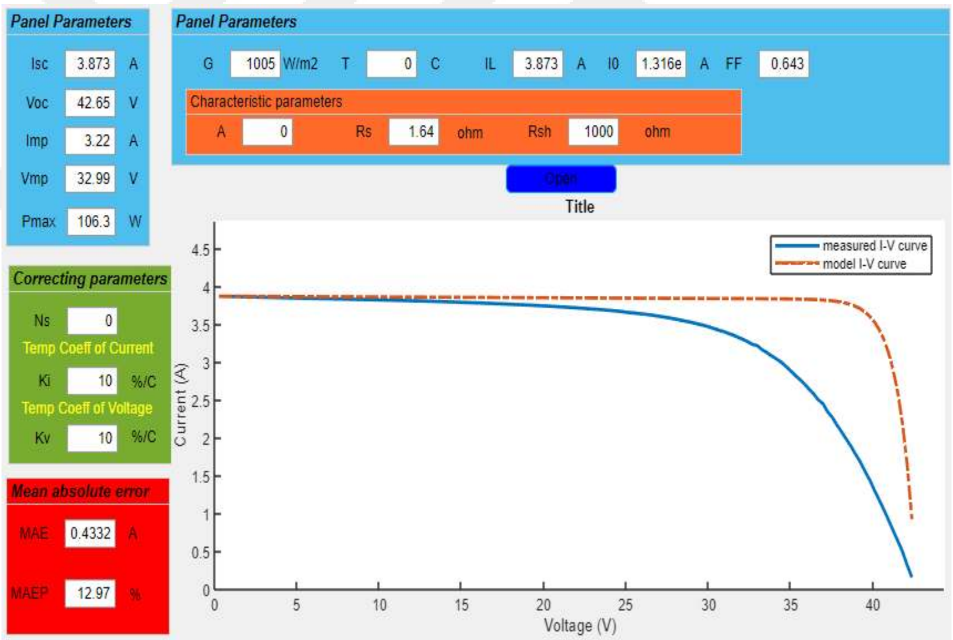


Figure 7.4 (SZ-100-36MFE: thin film) I-V characteristics.

Mean absolute error for current-voltage 0.4332A (12.97%).

7.2 Results and Discussions

The connection between output current and voltage is represented by the I-V characteristic curve of a typical solar cell, which encapsulates the essential electrical characteristics of a PV cell or module. Voltage (V) is decreased as the temperature of the solar cell increases, while current (I) is controlled by the quantity of solar radiation (insolation) reaching the cell (V). DC current is produced by solar panels, and its power is proportional to its voltage times it’s current. The I-V characteristic curve of a solar cell or module illustrates the device's operation by describing the relationship between current and voltage under radiant current conditions and at standard temperature. A solar array may be configured to generate energy as close as possible to its maximum power point using the information from the I-V curves (MPP). PV system losses have a significant influence on solar modules' efficiency and output capacity. By using best practices for solar module design and installation, these losses might be reduced.

So, the difference in the Figures (7.2), (7.3), and (7.4) are because of the losses that occur in solar PV, and these losses could be divided into the following reason:

1) Shading loss

The PV modules' performance will be negatively impacted when they are shadowed by certain structures, trees, or other things. Due to shade, energy loss might range from 10% to 70%.

Since the solar cells are linked in groups such that the same current travels through the cells in the group, if one cell is partly shaded, it will prohibit a portion of the current flow. As a consequence, the whole PV module's output will be impacted. If there is no electronic protection in place, hot spots may also develop and harm the PV modules in addition to the abrupt reduction in power output.

Continuous maintenance and good design will ensure that the PV modules are not overshadowed by shade. Thus, it can reduce the value of these losses.

Long-range shading is known as “soft shading” and is caused by cloud cover and is calculated taking into account the geographical location in the design stage. They are not as dangerous as shadows cast by nearby objects because they produce a more diffused light.

2) Dust losses

Refers to energy losses due to the accumulation of dust, snow, dirt, bird droppings and many other particles on the surface of PV modules installed at a low pitch angle. The amount of dust accumulated on the surface of the PV modules can affect the total power output of the PV module on a daily, monthly, seasonal and yearly basis. Energy losses due to pollution and dust are estimated at 2% of the total energy losses.

This average value varies widely according to geographic location. 2% energy loss is roughly adequate for a country with year-round rain, but for locations with long dusty seasons like Iraq for example, this number can easily reach 6 or 7% - this amount of energy loss is not insignificant.

3) Optical losses in solar modules

Photons of light interact with the p-n junctions of the crystal structure of solar cells, and the solar cells generate electricity. PV losses occur when light is reflected off the surface of the PV modules rather than absorbed to interact with the electrons.

This is definitely a feature of PV module design and is a subject of continuous research to improve the efficiency of PV modules. The challenge is to reduce the surface reflectivity of the PV modules while increasing the light absorption.

4) Spectral response of solar cells

Solar cells do not use all of the wavelengths transmitted by the sun. There are many frequencies, mostly 4% ultraviolet, 43% visible light, and 54% infrared.

Solar cells can convert half of the infrared radiation and most of the visible light, with a little bit of the rest. Manufacturers seek to increase electrical output by optimizing PV modules to give a general wide response to wavelengths.

5) PV energy loss due to radiation level

It represents the degradation of efficiency when the irradiance is reduced from an STC rating of 1000 W/m2 to a low radiance of 200 W/m2.

These losses are averaged for practical purposes at 1.5%, the efficiency drops and a value is used to compensate for the energy loss at the design stage and over the life of the PV module system.

6) Thermal loss of PV cells

The solar cell loses 0.5% of its output per single degree Celsius above the estimated STC temperature of 25 degrees Celsius, mostly due to a property inherent in the solar cell structure. High temperature power loss is one of the biggest losses in PV modules.

The effect of site-specific temperature on the performance of PV modules on site is often calculated using temperature coefficients. The temperature coefficients are open circuit voltage (Voc), short circuit current (Isc) and maximum power (MPP or Pmax). The Figure below shows that the voltage is strongly affected by higher temperature values, as the open circuit voltage Voc decreases and the FF decreases, while the ISC short circuit current increases slightly as the temperature rises but not enough to compensate for the large voltage drop. The overall result is a decrease in Pmax with increasing temperature. Since STC conditions also include a radiation of 1000 W/m2, the diagram below shows that the ideal operating conditions for a solar cell are at low temperature with high radiation (Cano 2011).

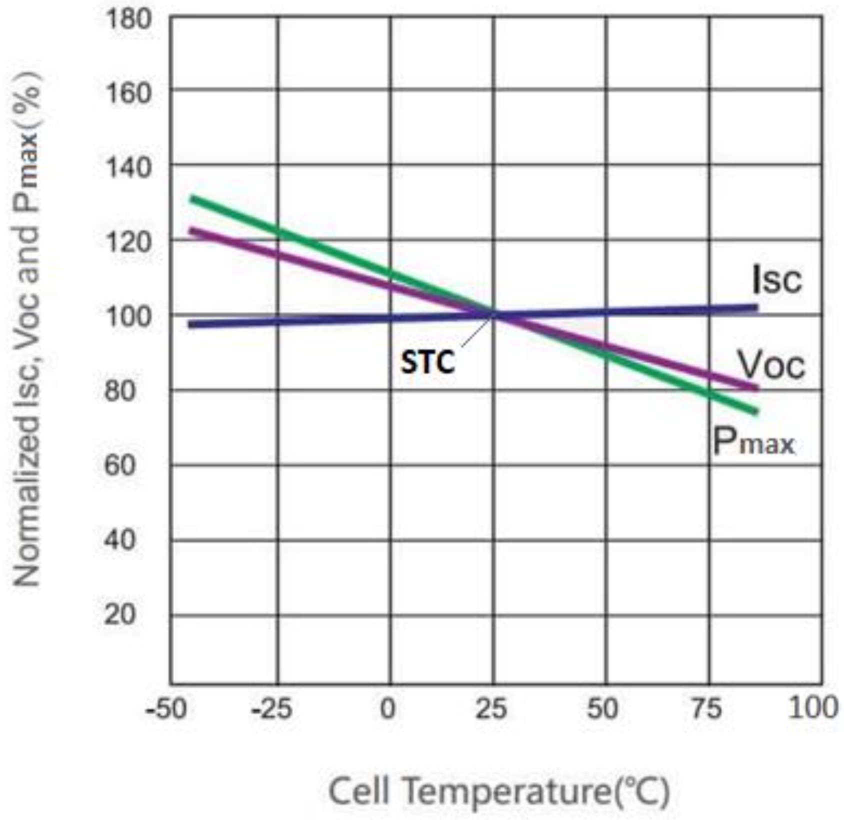


Figure 7.5 Effect of temperature on PV Cell Using temperature Coefficients (Cano 2011).

7) Loss of mismatch in solar modules

When the amount of PV power produced by two or more modules in one matrix is different, there is a mismatch between solar modules. This can happen in two ways, because of the partial shading already discussed, or through differences in the electrical properties of solar cells. Solar cell manufacturing varies as individual PV modules in the matrix simply do not perform the same. Complete chains may be mismatched due to poor guidance or situations in which different matrices face different directions. Apart from this, the paintings are not identical when manufactured. The tolerance ratio in error during the creation of PV modules in the factory is between +/- 1.5% to +/- 5%. This means that modules created mainly from these solar cells will not produce identical amounts of electrical energy. There are other causes of loss in, such as inflated diodes, partial dirt cover and thermal gradients between the groups or via the same PV module. Currently, the best solution is to use compact micro-reflective modules or install electronics at the PV panel or PV module level such as DC enhancers.

Table 7.4 Energy losses in the solar PV systems.

Cause of Energy Loss	Loss percentage	Design or Maintenance	Total Loss
Shadings	7%	Design and Maintenance	23.8% lost
Dust or Dirt	2%	Maintenance	
Reflection	2.5%	Only Design	
Spectral Loss	1%	Only Design	
Irradiations	1.5%	Only Design	
Temperature Losses	4.6%	Only Design	
Array Is mismatch	0.7%	Only Design	
Cable Losses (DC)	1%	Only Design	
Inverter Losses	3%	Only Design	
Cable Losses (AC)	0.5%	Only Design	

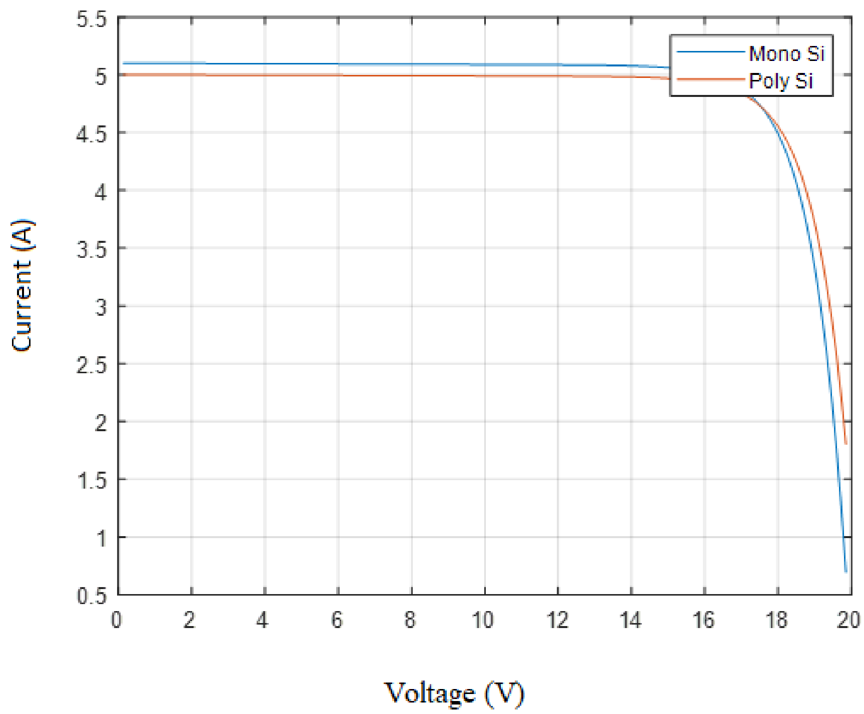


Figure 7.6 Mono-Si, and Poly-Si I-V curve.

There is a difference between the three curves above, which means that the previous losses affect the accuracy of the measurement, as a difference can be observed in the value of the maximum capacity extracted from the solar cells under the same measurement conditions.

It can be concluded from the three curves that the effect of losses is less on the (Mono-Si) PV modules compared to (Poly-Si and thin-film), and therefore the extracted power is greater and the efficiency is higher for the Mono-Si PV modules, which explains their high price.

Mono-Si cells have the highest efficiency then Poly-Si and thin-film.

8. CONCLUSION AND RECOMMENDATION

8.1 Conclusion

This project studied solar energy in terms of installing solar cells, defining the technology used in manufacturing them and their basic parameters, and then defining the components of solar modules and the standards that determine their performance. Three different PV technologies were compared: Mono-Si, Poly-Si and thin-films.

The results showed that the difference between (Mono-Si and Poly-Si) is relatively small, with an increase in Mono-Si efficiency and a longer lifespan. A graphical user interface has been created that describes the performance of solar cells, shows the relationship between current and voltage, and compares the three different types of solar cells.

In 2023, we definitely recommend modern Mono-Si solar modules. The only exception is the very limited budget profile, which probably only allows the purchase of old and cheap Poly-Si and not the standard Mono-Si PV modules.

If you are not constrained by the budget and want to achieve maximum service life and maximum power output over the life of the solar modules, and the area occupied by the solar array is important to you, choose Mono-Si solar modules.

8.2 Recommendation for Future Work

In the future, it is possible to work on designing hybrid solar modules to increase efficiency. This can be done by changing the range of solar cell parameters according to the characteristics of the cell.

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