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Dedication

وَكَانَ فَضْلُ اللَّهِ عَلَيْكَ عَظِيمًا

بسم الله الرحمن الرحيم والصلاة والسلام على ختام المرسلين

أتوج اليوم مسيرة سنوات من الجد والإجتهاد والسعي المتواصل في سبيل الحلم والعلم، وأقف على عتبات تخرجي لأقدم ثمرة جهدي وما وصلت إليه بعد فضل الله وتوفيقه الحمد لله، فبكل فخر أهديه إلى نفسي الشجاعة التي تحملت كل العثرات رغم الصعوبات، وإلى من كانوا مصدر الدعم والعطاء الدائم:

إلى من زين إسمي بأجمل الألقاب، إلى من علمني أن الدنيا كفاح وسلاحه العلم أبي شكرا لك بحجم السماء، ومن أبصرت بها طريق حياتي، القلب الحنون الذي كانت دعواتها تحيطني دوما وتسهل علي الشدائد أمي الحبيبة.

من كانوا الحضور الثابت في كل مرحلة السند الذي أستند عليه، بدعمكم تعلمت أن التعب لا يضيع وأن النجاح يولد من الوقوف الصادق، هذا اليوم يحمل أسمى لكن فخره ممتد إليكم إخوتي وأخواتي.

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المرابطين في غزة وكل فلسطين، أطفالا وكبارا حرمتهم الحرب من كل شيء جميل، أنتم بقلبي ودعائي لكم بالنصر.

دعاء

Dedication

وَكَانَ فَضْلُ اللَّهِ عَلَيْكَ عَظِيمًا

وآخر دعواهم: "الحمد لله رب العالمين."
لم تكن الرحلة قصيرة، ولا الطريق محفوفًا بالتسهيلات، لكنني تجاوزتها بعزم وصبر، فالحمد لله الذي
يسر البدايات وأتم النهايات وبلغنا الغايات
بكل حب أهدي ثمرة نجاحي

إلى العزيز الذي حملت اسمه فخراً واعتزازاً، وإلى معلمي الأول ومن أكرمني الله به وجعله بين صفوف
الرجال أبا لي وزادني شرفاً وعلواً ... إلى العظيم أبي.

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قوتي ونجاحي ... أمي الحبيبة.

إلى من قيل فيهم: (سَتَشُدُّ عَضُدَكَ بِأَخِيكَ). إخوتي، لم أصل لولا دعمكم وعطاؤكم بلا مقابل. فأنتم قوتي
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أثرٌ جميل في مسيرتي قبل تخرجي.

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النجاح.

وأخيراً.....

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List of abbreviations and nomenclatures

Symbol	Meaning
PV	Photovoltaic
ARC	Anti-reflecting coating
I_{sc}	Current of Short Circuit
V_{oc}	Voltage of Open Circuit
BIPV	Building Integrated Photovoltaic
STC	Standard Test Conditions
PSH	Peak Sun Hours
PSC	Partial Shading Condition
Θ	The tilt angle
FF	Fil Factor
P_{max}	Maximum Power
R_s	Series Resistance
R_{sh}	Shunt Resistance
G	Global Solar Radiation
A	Non-linear effect due to photocurrent
ROI	Return On Investment
GCPV	Grid Connected Photovoltaic systems
SAPV	Stand Alone Photovoltaic systems
Ω	Ohm- the unit of electrical resistance
MATLAB	MATrix LABoratory (Engineering Software)
GUI	Graphical User Interface

General

Introduction

General Introduction

In recent years the world has seen a marked growth in photovoltaic (PV) generation. PV generation is currently significant in many regions and it is expected to continue its exponential growth and to play a major role to meet renewable energy targets as set up by local authorities, national governments and international agreements to meet CO₂ reductions.

Currently, encouraging the use of renewable energy sources (RESs) for electricity generation is continually increasing in several countries around the world aiming to reduce the use of energy sources emitting greenhouse gas. Solar energy, one type of RESs, has been extensively used to produce electricity through the photovoltaic (PV) systems, especially over the past ten years, since it can mitigate climate change [1]. The concern related to global energy crisis and climate change threats from conventional sources of energy leads to look for alternate sources of energy. Solar energy is seen as a potential alternate source of energy as it is available globally in abundant. To develop an efficient and stable solar PV energy conversion...

Photovoltaic systems display nonlinear behavior and are significantly influenced by various external factors like solar irradiance and temperature, rendering their analysis and study challenging in real-world applications [2]. Thus, mathematical modeling and computer simulation are employed to depict the behavior of the photovoltaic generator and precisely evaluate its performance prior to real-world deployment [3].

The use of simulation tools in the field of solar energy has also become essential, as these tools allow for testing several operational cases and analyzing the impact of different parameters on the system, thus reducing cost and time compared to field experiments. In this context, our study aims to develop a simulator with a graphical interface that allows for the configuration and adjustment of photovoltaic (PV) generator parameters. This application aims to facilitate understanding the behavior of the PV system and enable the user to interactively study the effects of changes in radiation, temperature, and several other factors.

This work aims to combine mathematical modeling and software application in order to provide an effective educational tool for students and researchers in the field of renewable energies.

In order to structure this work, this dissertation is organized into three main chapters

- First chapter: This chapter presents the fundamental concepts related to photovoltaic solar energy. It introduces solar radiation, the structure and operating principle of a photovoltaic cell, and the different technologies used.
- Second Chapter: In this chapter, we present the mathematical models used to represent the behavior of a photovoltaic cell and generator. We detail the equivalent circuits, the characteristic equations, as well as the sizing methods for PV generators and some related studies.
- Third chapter: This chapter is dedicated to the practical part of the project. It describes the development tools used, as well as the design and implementation of the simulator with a graphical interface. We present the application's various functionalities, the parameterization of the photovoltaic generator, and the results obtained through the simulations.

Chapter I

Overview on the Photovoltaic systems

I.1 Introduction

Photovoltaic systems are considered among the most important renewable energy technologies used for generating electrical energy from solar radiation. This chapter aims to provide a general overview of photovoltaic energy by presenting the historical development of solar cells and the principle of photovoltaic effect, in addition to solar radiation and its different components. Furthermore, the concept of the photovoltaic cell, its manufacturing technologies, and its internal structure will be discussed, along with the main factors affecting the performance of photovoltaic systems. This study provides the theoretical background necessary for understanding the modeling and simulation of the photovoltaic generator in the following chapters.

I.2 Photovoltaic energy

Photovoltaic solar energy is a form of renewable energy that produces electricity by directly converting solar radiation through the photovoltaic effect, this phenomenon occurs at the level of the photovoltaic cell. Several cells are electrically interconnected to form a solar module. These modules are then grouped and wired together to constitute a photovoltaic array, as illustrated in (figure I.1) [4], that represents the power-generating unit of the installation.

The use of renewable energies has been widely growing in recent years in an attempt to reduce greenhouse gas emissions and limit global warming. Among the technologies that use renewable sources, photovoltaics is experiencing the fastest growth, driven by an increased efficiency of photovoltaic modules and a rapid decrease in prices. The coverage of PV systems has expanded in the built environment (BIPV), over land, agricultural fields (agri-voltaics), and even on water surfaces (floating PV). Understanding the principles behind this conversion and the factor that govern system performance is therefore essential to the design of reliable and efficient PV installations.

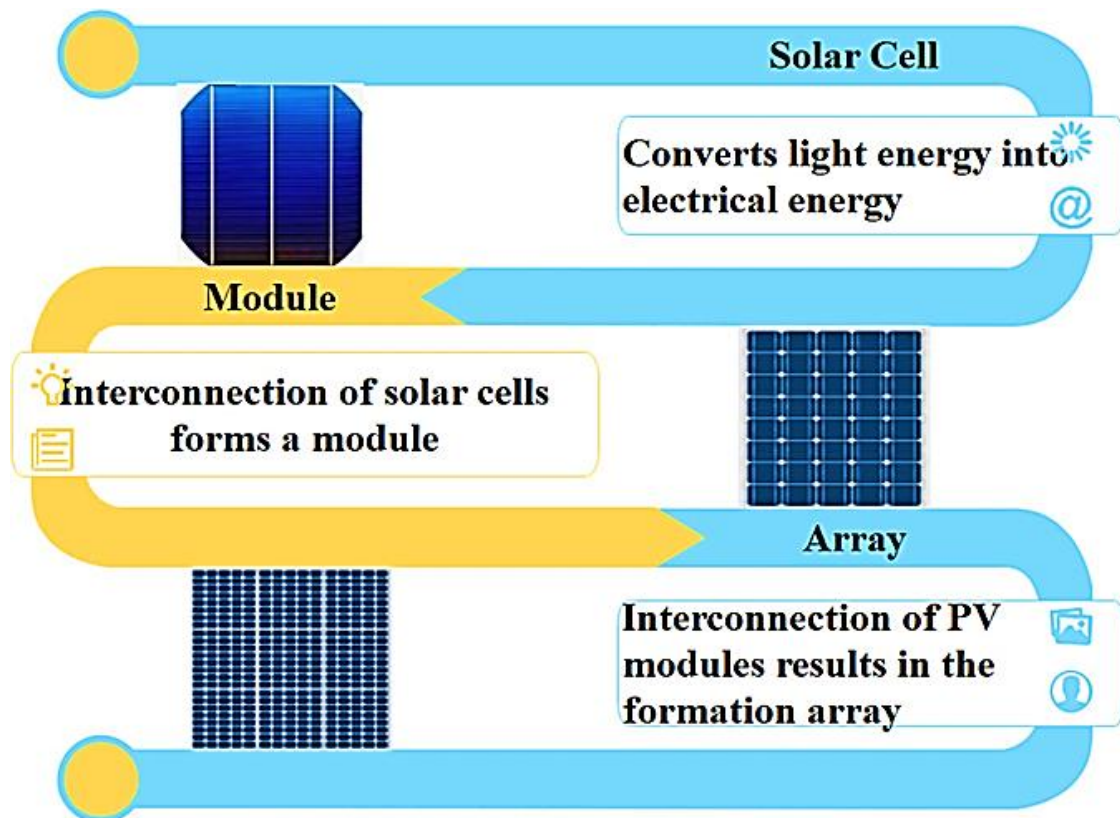


Fig I.1: Formation of photovoltaic (PV) cell, module, and an array [5].

I.3 Important dates in the history of photovoltaic

The history of solar photovoltaic cells begins with Edmond Becquerel's discovery of the photovoltaic effect in 1839. Becquerel found that when certain materials were exposed to light, an electric current was generated [6]. Then, Adams and Day found the photovoltaic properties of selenium in 1876. Planck proposed the quantum nature of light in 1900 [7]. Albert Einstein Thanks to his explanation of the photoelectric effect and his confirmation of the existence of "photons" as the driver of electron emission in 1905, Einstein was awarded the Nobel Prize in 1921 [8]. Thereafter Wilson gave the quantum theory of solids, relating the photon and the properties of solids in 1930. Mott and Schottky developed the theory of the solid-state diode after a decade [7]. The renowned research organization, Bell Laboratories, presented the world's first efficient silicon solar panel on April 25, 1954, with an efficiency of 6%. Applications of solar cells in satellites began in 1958 [9]. The economic crises of the 1970s, renewable energies, and in particular photovoltaic energy, which is emerging as one of the most promising sources of renewable energies [10]. After the development of PV technology and its use in the space applications, it is now being used for terrestrial applications [7].

I.4 The photovoltaic effect

The term "photovoltaic" is derived from two components: "photo"; originating from the Greek word for light, and "volta", in reference to the Italian physicist Alessandro Volta (1745–1827), who is credited with the invention of the electrochemical battery.

The photovoltaic effect is the direct conversion of solar radiation energy into electrical energy, achieved through cells composed of two doped silicon layers. To create a positive layer, the P-type layer; boron atoms are incorporated as dopants, while phosphorus atoms are incorporated to form the negative N-type layer. The junction between these two layers establishes a potential barrier. When a photon of sufficient energy is absorbed by the semiconductor, it breaks a valence bond, releasing a free electron and creating a positive hole, this phenomenon is known as the photovoltaic effect. The resulting potential difference between the two layers drives a movement of electrons through an external circuit, thereby generating an electric current.

I.5 The solar radiation

Solar radiation is the collection of electromagnetic waves emitted by the Sun. It consists of the full range of radiation, from far ultraviolet such as gamma rays to radio waves, including visible light [11]. The total radiation as measured on a horizontal plane must be divided into: direct, diffused and reflected components, as shown in (figure I.2).

I.5.1 Direct solar radiation

Direct beam radiation is point to point radiation from the sun directly to the panel [12].

I.5.2- The sky diffuse component

This is the component of radiation which falls on the PV as diffused radiation [12].

I.5.3- The ground reflected component

The component of the total solar radiation that is reflected of the ground is known as the ground reflected component [12].

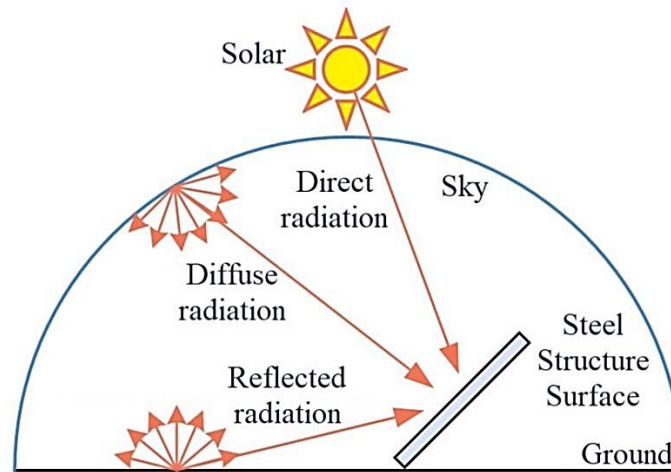


Fig I.2: basic solar radiation components [13].

I.6 Intensity of radiation

The hourly sums of direct and diffused solar radiation on receiving surface located horizontally to the surface of the earth under a clear sky are determined by: the latitude of the terrain, time and serial number of the day, the processes of refraction and absorption of direct and diffused solar radiation in the atmosphere by ozone, mixture of gases, water vapor, as well as Rayleigh and aerosol scattering of solar radiation.

To take into account the influence of the atmosphere conditions on the amount of incoming solar radiation flux, coefficients of atmospheric conditions are introduced, the values of which are determined on the basis of monthly average values of direct and diffused solar radiation per 1m^2 of the horizontal receiving area, obtained on the basis of long-term actinometrical measurements [14].

I.7 Concept of Photovoltaic cell

A Photovoltaic cell, also called solar cell, is an electronic component which converts the sunlight directly into electricity due to the photovoltaic effect. This physical phenomenon produces when the photons, the particles that consist the light hit the semi-conductor material and release electrons. The movement of these free electrons generates an electrical current.

I.8 Technologies of photovoltaic cells

In fact, most of solar cells worldwide are made from silicon, the traditional and first generation. One of the main reasons for this is the abundance of silicon on Earth, making it very inexpensive compared to other solar cell materials and technologies.

I.8.1 Monocrystalline silicon

Monocrystalline solar cells (figure I.3) are made from a single continuous crystal structure of silicon. The manufacturing process involves growing a single crystal of high-purity silicon, which is then sliced into thin wafers to form the basis of solar cells. Monocrystalline panels are recognized for their high efficiency and power output due to the uniformity and purity of the silicon crystal. The cells have a distinctive appearance with rounded edges and a uniform dark color [15].



Fig I.3: Mono-crystalline silicon solar cell [16].

I.8.2 Polycrystalline silicon

The polycrystalline silicon solar cells (figure I.4) are produced silicon wafers in molds of multiple silicon crystals rather than a single crystal in terms of condition of growth, it does not need to control like Monocrystalline Silicon cells, therefore, it is cheaper and less efficient (up to 19.2%) in comparison with Monocrystalline Silicon cells [17].

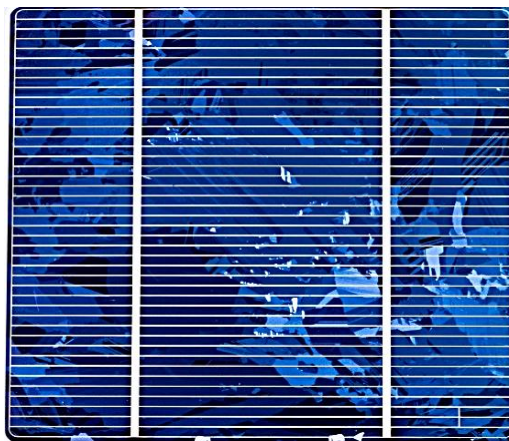


Fig I.4: Poly-crystalline silicon solar cell [18].

I.8.3 Amorphous crystalline silicon

In most devices, especially, in small electronic applications like calculators; amorphous silicon solar cell (figure I.5) is used. In this kind of silicon solar cells which is manufactured using grown silicon crystals, silicon is deposited as a thin layer onto a supporting substrate such as metal, glass or plastic. They are very small; therefore, the panel can be made flexible, and also their performance during low sunlight is better than crystalline panels. But, on the other hand, the amorphous panels are able to convert sunlight into electricity with less efficiency (10%), so they are not suitable for roof installation [17].

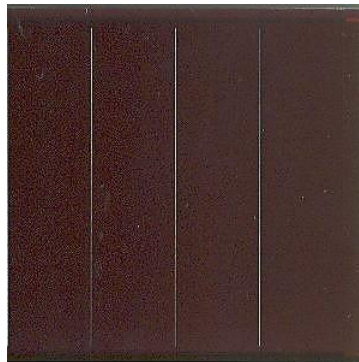


Fig I.5: Amorphous solar cell [19].

The following table (Table I.1) represents a comparison between the mentioned types of PV panels.

Table I.1: Comparison between types of PV panels [20].

			
Type of cells	Mono-Crystalline	Poly-Crystalline	Thin Film (Amorphous)
Glass color	Black	Blue	Brown, Grey, Black
Efficiency rate	20%	16%	10%
Lifespan	25 years	25 years	15-20 years
Advantages	Highly efficiency and durable	Lower cost	Less expensive
Disadvantages	Expensive	Less efficient	Lower efficiency and shorten Lifespan

I.9 The structure of the PV cell

As shown in the illustration below the solar PV panel is consists of layers made of different materials to perform different functions (figure I.6).

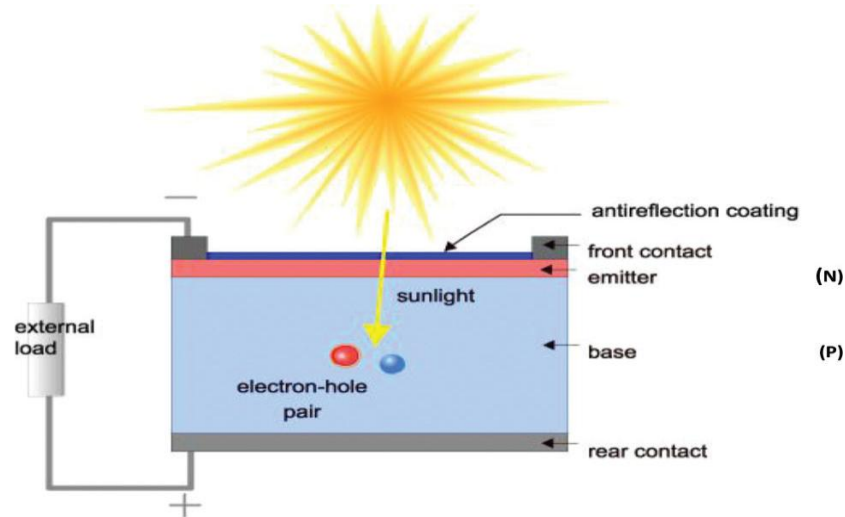


Fig I.6: Structure of Photovoltaic solar cell [21].

I.9.1 Anti-reflecting coating

Anti-reflecting coating (ARC) which is a very important part in solar cell fabrication. It is usually sprayed over bare silicon cell because silicon has a high surface reflection.

I.9.2 Front contacts

Front contacts that are necessary to collect the current generated by a solar cell. They are usually made of metals.

I.9.3 Emitter

An emitter that absorbs the incoming photons and transports their energies to the excited state of charge carriers. Pentavalent-doped silicon (n-type) has a higher surface quality than trivalent doped silicon (p-type), so it is placed at the front of the cell, where majority of the light is absorbed.

I.9.4 P-N junction

In p-n junction in its simplest form, the base (p-type) region is joined at a junction with emitter (n-type) region leading to majority electrons in the n-type side close to the junction to diffuse of to the p-type side and majority hole from the p-type to diffuse n-type side.

I.9.5 Rear contact

Rear contact is a less important than the front contact because it is much way from the junction and does not need to be transparent.

I.10 Advantages and challenges of PV energy

Solar energy has a number of advantages, including the following:

- ✓ Renewable Energy source: a clean, and non-polluting when function. And reduces the dependence to traditional resources.
- ✓ Possibility of different system connection: they can be operated as standalone systems or grid-connected.
- ✓ Creates job opportunities: in manufacturing, installation, and maintenance.
- ✓ Long operational lifespan: (Often between 20 and 25 years for panels).

Although these aspects demonstrate clear advantages, certain challenges require further investigation, some of which are briefly addressed:

- High initial cost of investment.
- Complexity of parameterization.
- Its dependence on climatic conditions.
- The need for regular maintenance.
- Intermittency: Lack of continuity (does not produce energy at night, requiring storage systems or backup sources).
- Difficulty of storage.
- It requires vast areas.

I.11 Factors Affecting Performance of PV energy

I.11.1- Solar Irradiance

Solar radiation directly affects the photovoltaic cell, as an increase in light flux leads to a shift in the current-voltage curve along the current axis, due to the direct proportionality between the short-circuit current (I_{sc}) and the intensity of the radiation. The increase in short-circuit current is much greater than the increase in open-circuit voltage (V_{oc}) (figure I.7). This is due to the linear change of the short-circuit current, while V_{oc} follows a logarithmic relationship with the intensity of radiation, this makes it less affected by its changes [22].

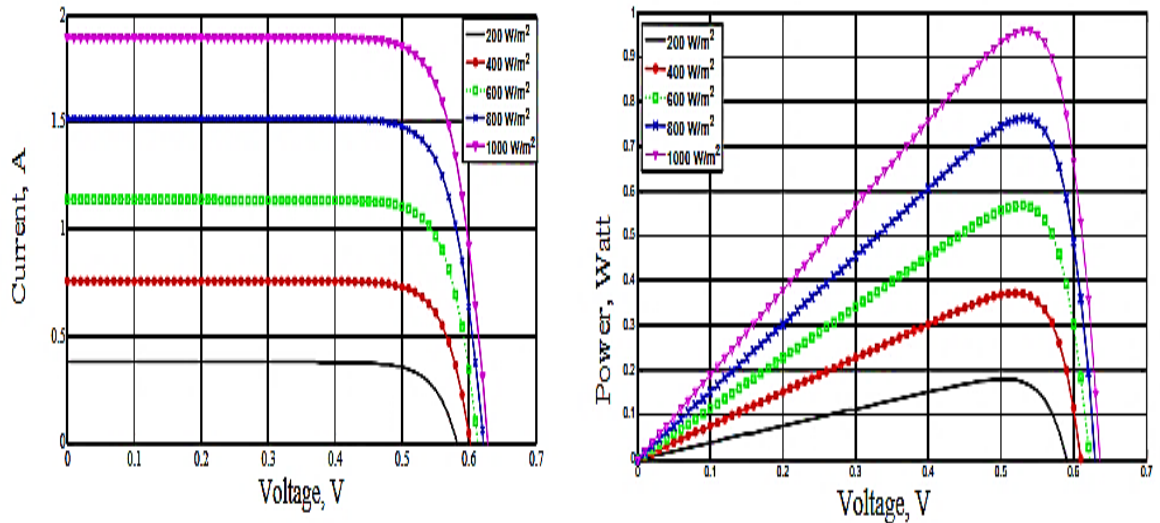


Fig I.7: The (I-V) and (P-V) Characteristic curves of solar panel, plotted at different irradiance levels and 25°C [22].

I.11.2 Temperature

The thermal environment in which a solar cell operates, plays a crucial role in determining its power output. Solar cells are typically designed to function optimally at a standardized temperature of 25 °C. However, an increase in the surrounding temperature leads to a decline in the effectiveness of the solar cell. The output voltage in a PV cell is operate significantly influenced by temperature, although the impact of temperature on the output of current is minimal (figure I.8). The lifespan and efficiency of a solar cell are reduced when it is at elevated temperatures on a continuous basis [23].

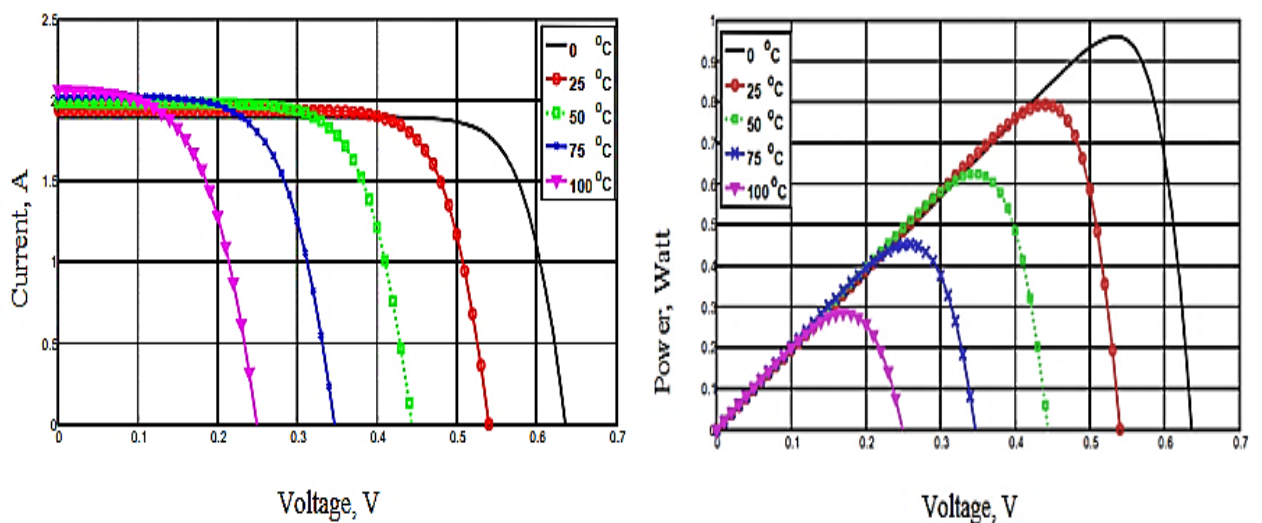


Fig I.8: Influence of temperature on the (P-V) and (I-V) characteristic of a solar cell under an irradiance of 1000 W/m² [20].

I.11.3 Shading

Another dominant environmental phenomenon is the partial shading condition (PSC) (figure I.9), which significantly impacts the PV output. In series and parallel combinations, the PV cells are connected to generate desired photon current at the correct voltage. The cells connected in series must hold the same current; not all of them produce equal photocurrents even in events such as partial shading. The shaded PV cells are reverse biased in these situations and act as a charge to the fully illuminated cells, storing power instead of producing it. The PV array output power is reduced due to mismatch loss which is the difference between the PV array row output power due to PSCs [24].



Fig I.9: PV Panel partially shaded [24].

I.11.4 Tilt Angle and Orientation

Maximum absorption of solar radiation occurs when the panel surface is perpendicular to direct sunlight ($0^\circ - \theta$) (figure I.10). Higher direct sunlight exposure on a surface perpendicular to the solar radiation results in increased energy production. Generally, the highest output performance of PV panels is achieved at low latitudes, especially when the latitude angle matches the panel's tilt angle and the module's orientation in the southern hemisphere (due north) or the northern hemisphere (due south). At higher latitudes, the highest output power is gained when the tilt angle is very close to minus 10 - 15% of the latitude angle [25].

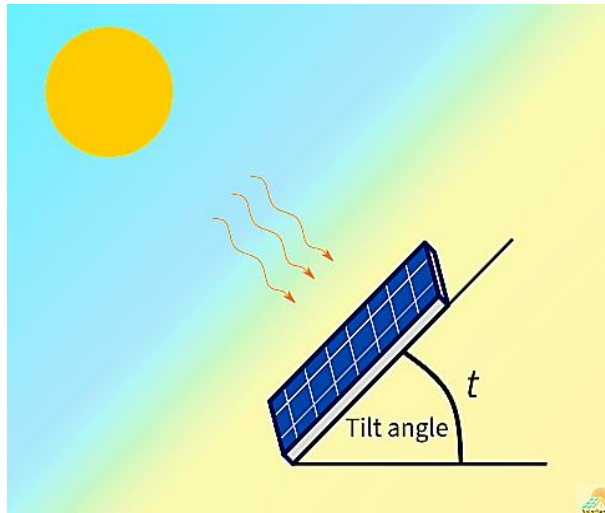


Fig I.10: The tilt angle [26].

I.11.5 Internal resistance

I.11.5.1 Series resistance

The series resistance in a photovoltaic cell arises from the ohmic resistance of the semiconductor material, metal contacts, and interconnections. It is typically small but plays a crucial role in determining the cell's output characteristics. Under load, an increase in series resistance causes a voltage drop inside the cell, leading to a reduction in the fill factor (FF) and maximum power output (P_{max}), while having little effect on the open-circuit voltage (V_{oc}). Consequently, the (I-V) curve becomes flattened near the knee point, resembling ohmic behavior in extreme cases. Minimizing R_s is therefore essential for efficient cell operation [22].

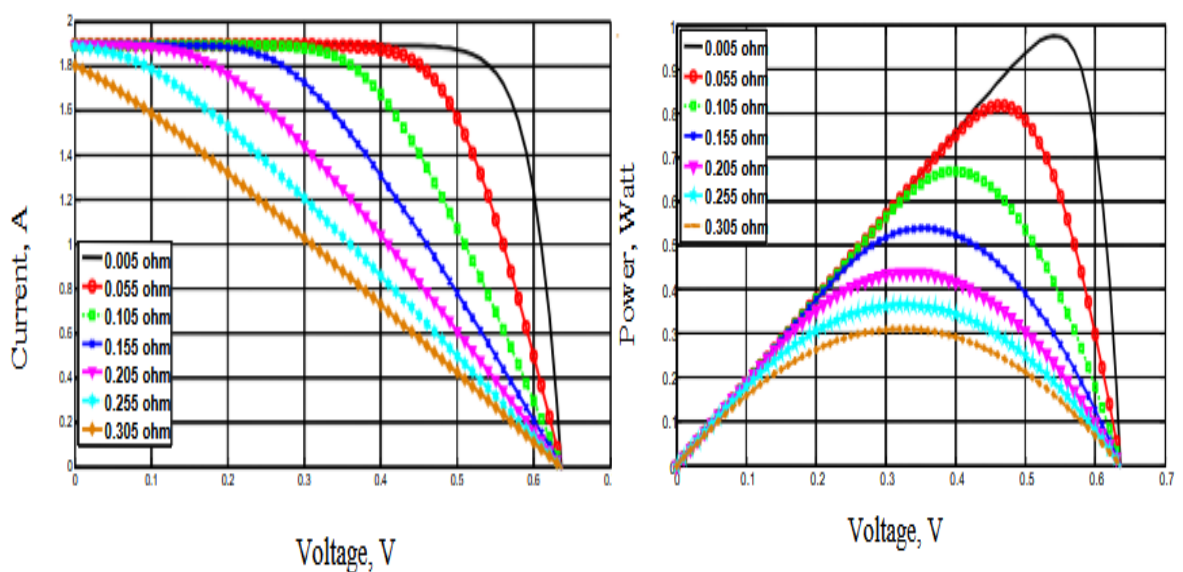


Fig I.11: (I-V) and (P-V) characteristic curves, plotted at different series resistance values[22].

I.11.5.2 Shunt resistance

Shunt resistance arises primarily from manufacturing defects, representing leakage paths across the p-n junction. In well-made cells, R_{sh} is generally very large. A low shunt resistance provides an alternate path for the photocurrent, reducing junction current and causing a drop in output voltage and power, with a steeper current fall near the short-circuit region and a reduced fill factor. Its influence is most significant at low voltages, where the effective cell resistance is high. Beyond a certain threshold typically; around $50\ \Omega$, electrical parameters such as I_{sc} , V_{oc} , P_{max} , and FF stabilize. Therefore, maximizing R_{sh} is essential to minimize leakage losses and preserve cell performance [20].

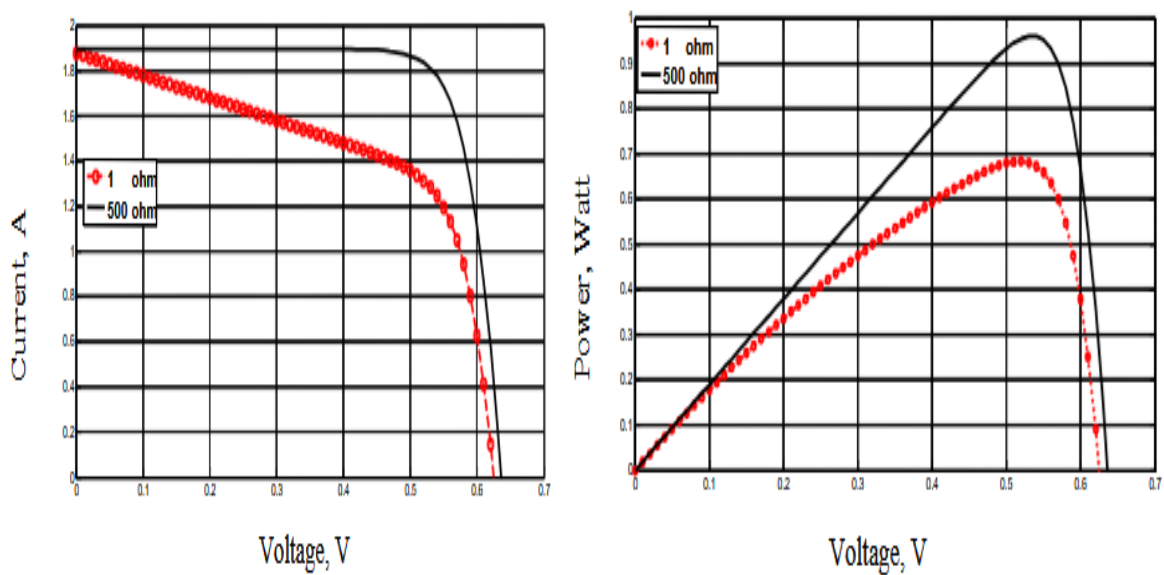


Fig I.12: (I-V) and (P-V) characteristic curves, plotted at different shunt resistance values [22].

I.11.6 Dust

Wind and atmospheric pollution lift dust particles and disperse them into the atmosphere; as wind speed increases, greater quantities of dust are suspended in the air, while the rate of gravitational settling decreases. Dust settlement depends primarily on particle properties such as chemical composition and size, as well as prevailing environmental conditions. Excessive dust accumulation leads to degradation of the solar cell's conversion efficiency and fill factor, causing PV module performance to decline exponentially. High humidity promotes the formation of dew on the module surface, facilitating dust adhesion and coagulation. Modules installed at larger tilt angles accumulate less dust, resulting in a smaller reduction in light transmittance. Additionally, finer dust particles affect PV efficiency more significantly than coarser ones [27].

I.11.7 Wind velocity

The wind velocity affects PV cell performance primarily by cooling the cell surface, reducing cell temperature, which leads to improved efficiency since higher temperatures generally decrease PV cell output. Increased air velocity enhances convective heat transfer, thereby lowering the cell temperature [27].

I.11.8 Humidity

Humidity decreases the irradiance received by the PV cells due to scattering and diffraction of sunlight by water vapor particles, leading to reduced short circuit current and overall efficiency. Moreover, high humidity can cause moisture ingress into the cell, resulting in performance degradation over time. Interestingly, higher wind speeds can reduce ambient humidity levels, indirectly improving PV efficiency, but may also increase dust deposition which negatively affects performance [27].

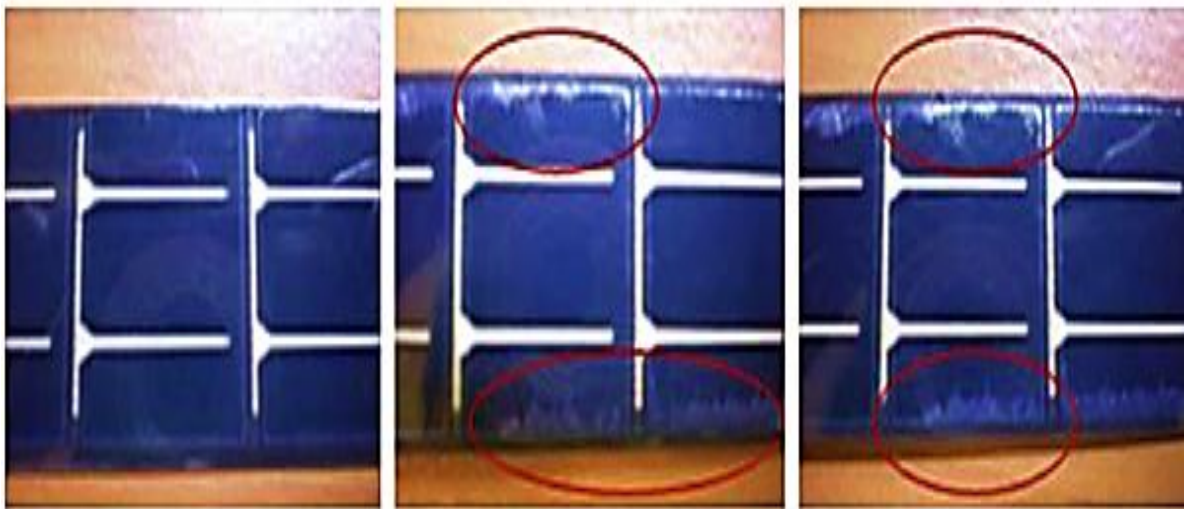


Fig I.13: Delamination of encapsulant after prolonged hours of humidity test [28].

I.12 Conclusion

In conclusion, this chapter has provided a comprehensive overview of photovoltaic energy and its related concepts. The historical development of solar cells and the photovoltaic effect have been discussed, along with solar radiation and its main components. The concept of the photovoltaic cell and its internal structure have been presented, highlighting the key advantages and challenges of photovoltaic energy systems.

In addition, the main factors affecting the performance of a photovoltaic generator, such as solar radiation, temperature, dust, and other environmental conditions, have been examined due to their direct impact on system efficiency and stability. This theoretical study has established the necessary scientific foundation for understanding the modeling and simulation of photovoltaic generators, which will be addressed in the following chapter.

Chapter II

Modeling and Sizing of PV generator

II.1 Introduction

Having explored of photovoltaic energy, it becomes essential to study the electrical behavior of solar cells and modules through mathematical modeling and experimental analysis. Modeling is considered one of the most important scientific methods that helps understanding the behavior of solar cells and photovoltaic modules and predicting their performance under various operating conditions.

This chapter aims to examine the electrical model of a solar cell and analysis its key electrical characteristics. It will also address methods for connecting the cells and modules, both in series and parallel, and their impact on the electrical characteristics of the photovoltaic generator. Furthermore, it will present methods for determining the size of a PV generator based on energy requirements and climatic conditions. This study is a fundamental step towards understanding how to improve the performance of these systems and ensure their stability and efficiency in various applications.

II.2 Modeling of the PV cell

The photovoltaic cell has a non-linear $I(V)$ characteristic (figure II.1). The characteristic of a photovoltaic cell sweeps across 3 of the 4 existing quadrants [29]. A PV cell is a load in quadrant (B) and quadrant (C). Operation in these two quadrants is not recommended because there is a risk of destruction due to localized heating. Operation in quadrant (A) is normal; in this case: the cell is a generator and therefore produces energy.

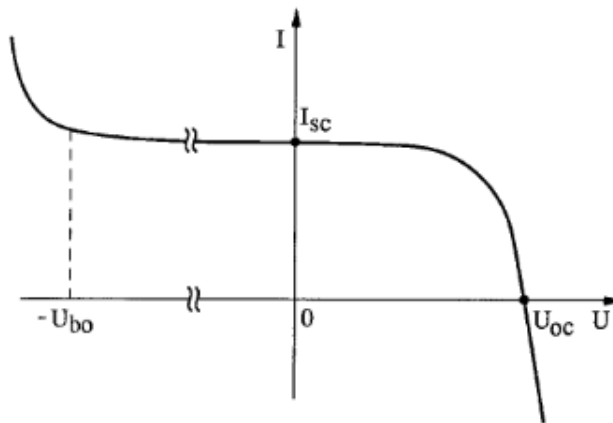


Fig II.1: $I(V)$ curve of characteristics of a photovoltaic cell.

There are several electrical models, used by researchers, describing the physical behaviors of PV cells.

II.2.1 Circuit Models for photovoltaic cell

II.2.1.1 Ideal model

An ideal Photovoltaic cell consists of a single diode connected in parallel with a light generated current source I_{ph} (figure II.2), where its output current I , can be written as:

$$I = I_{ph} - I_d \quad (II.1)$$

The photocurrent I_{ph} is considered equivalent to the current short-circuit current I_{sc} , with $V_{pv} = 0$.

$$I_{ph} = [I_{sc} + K_i * (T_c - T_{ref})] * \frac{G}{G_{ref}} \quad (II.2)$$

Where:

K_i is the cell circuit temperature coefficient (Amperes/K),

T_c is the cell temperature in Kelvin,

T_{ref} is the reference temperature in Kelvin, equals to (298.15 K),

G determines the solar irradiance incident on the PV array, expressed in (W/m^2),

G_{ref} is the reference solar irradiance, defined under solar test conditions ($1000 W/m^2$).

$$I_d = I_s \left[\exp\left(\frac{V_d}{V_t}\right) - 1 \right] \quad (II.3)$$

Where:

I_d is the diode current,

I_s is the diode saturation current;

V_d is the diode voltage,

V_t is the thermal voltage ($\frac{k*T_c}{q}$),

K is the constant of Boltzmann ($1.38 \cdot 10^{-23} J/K$),

Q is the charge of the electron ($1.6 \cdot 10^{-19} C$).

From the expressions described above, we can deduce the current delivered by a cell in the ideal case as follows:

$$I = I_{ph} - I_s \left[\exp\left(\frac{V}{V_t}\right) - 1 \right] \quad (II.3)$$

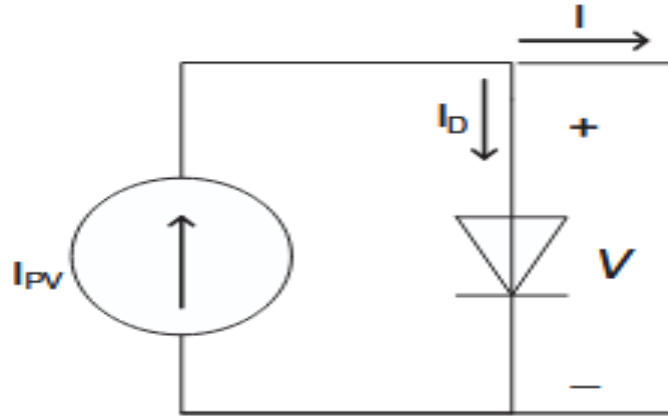


Fig II.2: Ideal PV circuit model [30].

II.2.1.2 Real model

a) Photovoltaic Model with Series Resistance:

The photovoltaic cell model with series resistance (model R_s) shown in (figure II.3) is achieved by adding the series resistance R_s . Therefore, the output current can be as follows:

$$I = I_{ph} - I_d \quad (II.4)$$

And:

$$I = I_{ph} - I_s \left[\exp \left(\frac{V + R_s I}{A V_t} \right) - 1 \right] \quad (II.5)$$

Where:

I is the current delivered by the photovoltaic cell,

I_{ph} is the photocurrent.

The photocurrent I_{ph} :

This is the current generated by a cell; it is proportional to solar irradiation and is slightly influenced by temperature according to the following equation:

$$I_{ph} = [I_{sc} + K_i * (T - T_{ref})] * \frac{G}{G_{ref}} \quad (II.6)$$

With:

I_{sc} is the short-circuit current (as specified by the manufacturer), in [A],

K_i is the short-circuit current divided by the panel temperature coefficient, in [A/K],

T is the ambient temperature, in [K].

The saturation current I_s :

This current varies with temperature and it is given by:

$$I_s = I_{rs} \left(\frac{T}{T_{ref}} \right)^3 \exp \left[\frac{qE_g}{AK} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right] \quad (II.7)$$

With:

E_g is the band gap energy of the semiconductor, expressed in [eV], equal to 1.12 eV for polycrystalline silicon at 25°C), and A is the ideality factor, without unit.

The reverse saturation current of the diode (leakage current) I_{rs} :

Its expression is given by the equation:

$$I_{rs} = \frac{I_{sc}}{\exp\left(\frac{qV_{oc}}{KAT}\right) - 1} \quad (II.8)$$

Where: V_{oc} is the open circuit voltage of the module (as specified by the manufacturer), in [V].

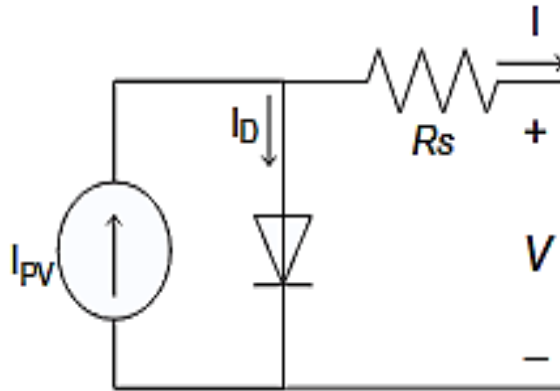


Fig II.3: Circuits model for PV cell with series resistance [30].

When the leads from the PV cell are left open, $I = 0$ and we can solve (II.2) for the open-circuit voltage V_{oc} [31]:

$$V_{oc} = \frac{KT}{q} \ln \left(\frac{I_{ph}}{I_s} + 1 \right) \quad (II.9)$$

b) Photovoltaic Model with Series and shunt Resistances:

Equation (II.5) does not adequately represent the behavior of the cell when subjected to environmental variations, especially at low voltages. A more practical model can be seen in (figure II.4), where series R_s , and parallel resistances R_{sh} , are introduced. An output current equation using this model can be written as [30]:

$$I = I_{ph} - I_d - I_{sh} \quad (\text{II.10})$$

$$I = I_{ph} - I_s \left[\left(\exp \left(\frac{V + IR_s}{AV_t} \right) - 1 \right) \right] - \frac{V + IR_s}{R_p} \quad (\text{II.11})$$

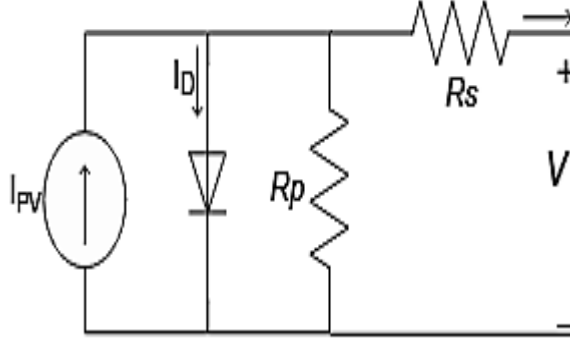


Fig II.4: PV circuit model with series and parallel resistance [30].

II.2.1.3 Model of two parameters

The idea in this model is based on the fact that under standard conditions, the current of a PV module can be expressed as a function of the voltage, by an expression containing a single simplified exponential as shown in equation below [32]:

$$I = I_{sc} \left\{ 1 - C1 \left(\exp \left(\frac{V_n}{C2 V_{oc}} \right) - 1 \right) \right\} \quad (\text{II.12})$$

The two parameters $C1$ and $C2$ are calculated as a function of I_{mp_n} , V_{mp_n} , V_{oc_n} and I_{sc_n} under standard conditions:

$$C1 = \left(1 - \frac{I_{mp}}{I_{sc}} \right) \exp \left(\frac{-V_{mp}}{C2 V_{oc}} \right) \quad (\text{II.13})$$

$$C2 = \frac{V_{mp}/V_{oc}^{-1}}{\log \left(1 - \frac{I_{mp}}{I_{sc}} \right)} \quad (\text{II.14})$$

Where:

I_{mp} is the maximum power current under (STC) in (A).

V_{mp} is the maximum power voltage under (STC) in (V).

II.3 The photovoltaic module

The cell is the basic component of a photovoltaic module, and it represents a low-power photovoltaic generator. Therefore, photovoltaic modules are made by combining a large number of basic cells in series and/or parallel to increase the power produced.

II.3.1 Series association

Connecting ns cells in series increases the voltage of the photovoltaic module. The cells then carry the same current, and the characteristic curve resulting from the series connection is obtained by adding the individual voltages of each cell, as shown in (figure II.5).

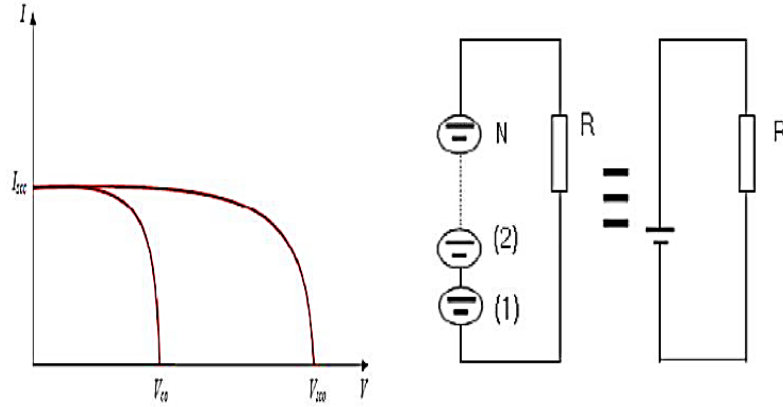


Fig II.5: Characteristics resulting from a grouping of ns cells in series.

Equation (II.9) represents respectively the open-circuit voltage (V_{oc}) and the short-circuit current (I_{sc}) of a series association of ns cells.

$$V_{oc} (pv) = ns * V_{oc} (cell), \quad I_{sc} (pv) = I_{sc} (cell) \quad (II.15)$$

II.3.2 Shunt association

Connecting np cells in parallel increases the total output current of the PV array string. In a group of identical cells connected in parallel, the cells are subjected to the same voltage and the characteristic resulting from the grouping is obtained by adding the currents, see (figure II.6).

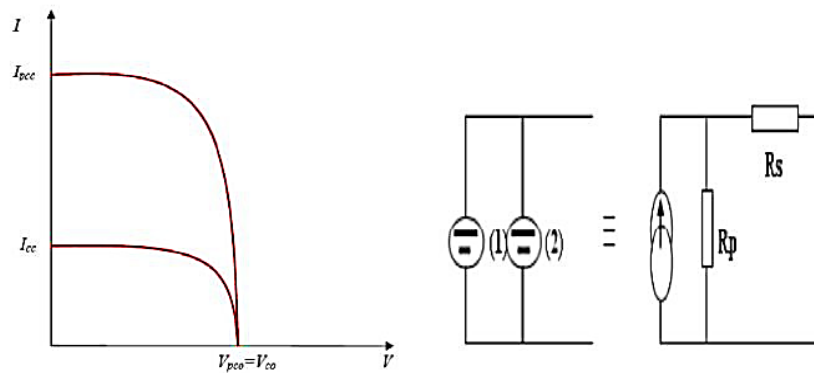


Fig II.6: Characteristics resulting from a grouping of np cells in shunt.

Equation (II.11) represents respectively the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of a parallel association of np cells.

$$I_{sc} (pv) = np * I_{sc} (cell), \quad V_{oc} (pv) = V_{oc} (cell) \quad (II.16)$$

II.4 Modeling the performance characteristics of a PV module

The important electrical characteristics of a PV module are the short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and maximum output power (P_{max}) as a function of sunlight and PV module temperature.

II.4.1 The short-circuit current

The short-circuit current of a photovoltaic module is defined as the current generated when the module terminals are connected directly without an external load. At normal solar irradiance levels, the short-circuit current can be considered approximately equivalent to the photocurrent generated within the photovoltaic cell, which is directly proportional to the solar irradiance intensity (G). However, this linear assumption can sometimes lead to discrepancies between theoretical values and experimental measurements. To account for the nonlinear behavior associated with photocurrent generation, a power law relationship with an exponential coefficient α , is employed, allowing for a more accurate representation of the solar irradiance effect [33]. Therefore, the short-circuit current of the PV module can be easily calculated using the following relationship:

$$I_{sc} = I_{sc_{ref}} \left(\frac{G}{G_{ref}} \right)^\alpha \quad (II.17)$$

Where:

$I_{sc_{ref}}$ is the short-circuit current of the PV module under standard sunlight G_{ref} , while

I_{sc} is the short-circuit current of the PV module under solar radiation G ,

α represents non-linear effects due to photocurrent.

II.4.2 The open-circuit voltage

The open-circuit voltage of a PV module corresponds to the voltage across the module when no load is connected to it. The relationship between open-circuit voltage and solar irradiance is represented by a logarithmic function based on the ideal diode equation. The effect of temperature on open-circuit voltage results in an exponential increase in saturation current

with temperature [34]. This leads to some difficulties in understanding the observed behavior of PV modules in real-world operation.

Additional conditions or correction parameters must be introduced to account for shunt resistance, series resistance, and diode non-ideality. Based on the model given by Van Dyk [35] and taking into account the effect of temperature, the open-circuit voltage, for a given irradiance and temperature, can be expressed as:

$$V_{oc} = \frac{V_{ocref}}{1+b*\ln(G_{ref}/G)} \left(\frac{T_{ref}}{T} \right)^\gamma \quad (II.18)$$

Where:

V_{oc} is the open-circuit voltage of the PV module under solar radiation,

V_{ocref} is the open-circuit voltage of the PV module under standard sunlight,

γ represents the non-linear effects of temperature on voltage and b represents a dimensionless technological constant of the module [35].

II.4.3 The fill factor

The fill factor measures the deviation of the actual current-voltage (I-V) characteristic from the ideal characteristic. PV modules typically have an associated parasitic resistance (R_s) and a parasitic resistance (R_{sh}). Both types of parasitic resistance contribute to reducing the fill factor. The fill factor is expressed by the following relationship [36].

$$FF = FF_{ref} \left(1 - \frac{R_s}{v_{oc}/I_{sc}} \right) \quad (II.19)$$

$$FF_{ref} = \frac{v_{oc} - \ln(V_{oc} + 0.72)}{1 + v_{oc}} \quad (II.20)$$

Where:

FF_{ref} is the fill factor of the ideal PV module without resistive effects.

R_s is the series resistance.

v_{oc} is the normalized value of the open-circuit voltage to the thermal voltage, it is equals to:

$$v_{oc} = \frac{V_{oc}}{nkT/q} \quad (II.21)$$

Where: n is the ideality factor ($1 < n < 2$).

The fill factor is a dimensionless parameter used to assess the quality of a photovoltaic module. It can also be defined as the ratio between the maximum output power and the product of the short-circuit current and the open-circuit voltage of the module.

$$FF = \frac{P_{max}}{V_{oc} * I_{sc}} \quad (II.22)$$

II.4.4 Maximum power-output

Making use of the definition of the fill factor, the maximum power output P delivered by the PV module can be written as:

$$P_{max} = FF * V_{oc} * I_{sc} \quad (II.23)$$

The relationship the short circuit current and open circuit voltage of PV module is given by the following relationships respectively:

$$I_{sc}(t) = [I_{sc, stc} + K_i(T_m(t) - 25)] \cdot \frac{G(t)}{1000} \quad (II.24)$$

$$V_{oc}(t) = V_{oc, stc} - K_v * T_m(t) \quad (II.25)$$

Where:

K_v is the open-circuit voltage temperature coefficient, in (V/°C).

$T_m(t)$ is the average temperature of the module. It is given by the expression:

$$T_m(t) = T_{amb}(t) + \left(\frac{T_{NOCT} - 20}{800} \right) * G(t) \quad (II.26)$$

Where:

T_{NOCT} is the nominal temperature of the cells when operating at open circuit, ambient temperature of 20°C at AM 1.5 and irradiance of $G = 0.8 \text{ kW/m}^2$ and wind speed not greater than 1 m/s, in [°C].

II.5 Literature review

A. Abdulrazzaq et al. (2025) proposed a hybrid GA–PSO method for extracting the five SDM parameters from measured I-V curves, where PSO is used to optimally tune the GA control parameters rather than setting them empirically. Among three evaluated objective function formulations, the implicit form of the SDM yielded the best accuracy. The study also established that using only 20–30 I-V data points per curve reduces computational cost by over 60% with negligible accuracy loss. Validated across monocrystalline, poly-crystalline, and

amorphous PV samples, the method outperforms several published approaches in both accuracy and convergence speed [38].

M. Nfaoui et al. (2024) developed a comprehensive modeling and simulation framework for PV system performance within a MATLAB/Simulink environment, based on a single-diode equivalent circuit model applied to a polycrystalline silicon PV module (Aleo Solar 150 S). The model was validated against PVsyst software, demonstrating high predictive accuracy. A key contribution of this work is the integration of wind speed as an additional meteorological parameter alongside irradiance and temperature, as presented in (figure II.7) showing its significant influence on PV cell temperature and overall system efficiency. The study confirms that incorporating multifactorial meteorological parameters into PV modeling substantially enhances simulation fidelity and performance prediction under varying climatic conditions [39].

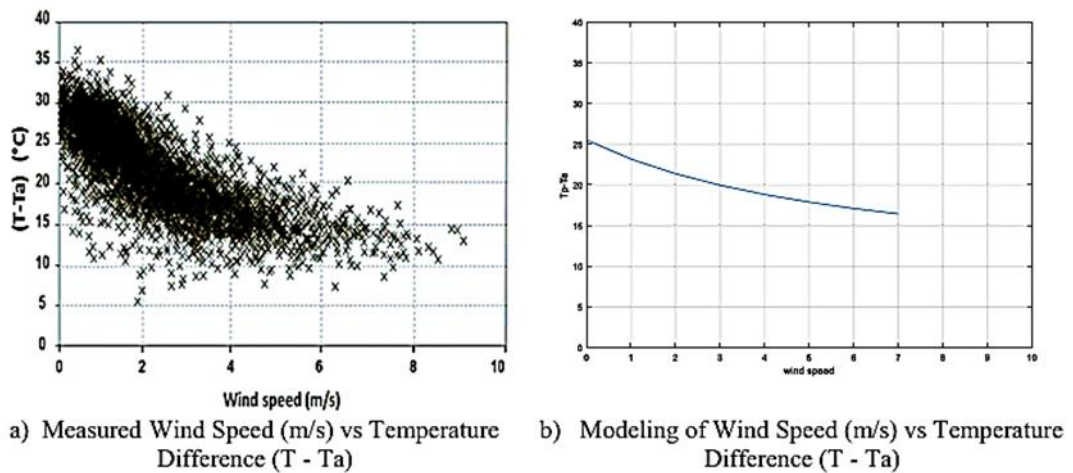


Fig II.7: The relationship between $(T - T_a)$ and the wind speed for an irradiation of 800 W/m^2 [39].

A. Nordin et al. (2020) developed a MATLAB GUIDE-based GUI platform for sizing a grid-connected PV system, structured across multiple interface windows covering load analysis, PV array sizing, tariff calculation, costing, and return on investment (ROI). The sizing methodology integrates key correction factors including temperature effects, wiring losses, and inverter efficiency, computing energy production based on Peak Sun Hours (PSH). Results showed strong agreement with manual calculations, confirming the tool's reliability. The authors emphasized that such graphical tools simplify complex PV engineering calculations and make system design accessible to non-specialists [40].

Grid-Connected Photovoltaic

Step A

PV Module Rated DC Power Output (W)	300
Manufacturer Power Guarantee	0.97
Number of Modules in Array	4
Array Guarantee Power Output (W)	TOTAL

Step B

Array Avg. Operating Temperature (°C)	35
Temperature Coefficient for Power	0.0045
Standard Test Condition Temperature (°C)	25
Temp-Corrected Array Power (W)	TOTAL

Step C

Array Wiring and Mismatch Losses	0.03
Net Array Power Output (W)	TOTAL
Inverter Maximum Dc Power Rating (W)	TOTAL

Step D

Inverter Power Conversion Efficiency	0.92
Inverter MPPT Efficiency	1.00
Inverter Maximum AC Power Output (W)	TOTAL

TOTAL

Average Daily Insolation (PSH)

4

Average Daily Energy Production (Wh/day)

day

Average Monthly Energy Production (kWh)

month

Calculate

Next

FORMULA

Back

Fig II.8: The grid-connected photovoltaic tab [40].

S. Alsadi and T. Khatib (2018) provide a comprehensive review of the development of the sizing of photovoltaic power systems encompassing both standalone photovoltaic systems (SAPV) and grid-connected photovoltaic systems (GCPV), and constitutes one of the primary references upon which the present work is based. A central finding of this review is that accurate modelling of PV system components is a fundamental prerequisite for reliable sizing. In particular, PV module modelling and battery system modelling play a decisive role in predicting system performance over time. It also highlights the role of simulation software in facilitating and accelerating the sizing process. The availability of dedicated optimization software packages has made the design process more systematic and less dependent on manual iterative calculations [41].

M. B Eteiba et al. (2013) developed a MATLAB/GUI-based simulation and monitoring model for PV cells, modules, and arrays, grounded in fundamental circuit equations and accounting for the effects of solar radiation and temperature variations in real time as show in (figure II.9). The Newton-Raphson method was applied to solve the model equations, and results demonstrated the significant influence of these climatic factors on PV output power [42].

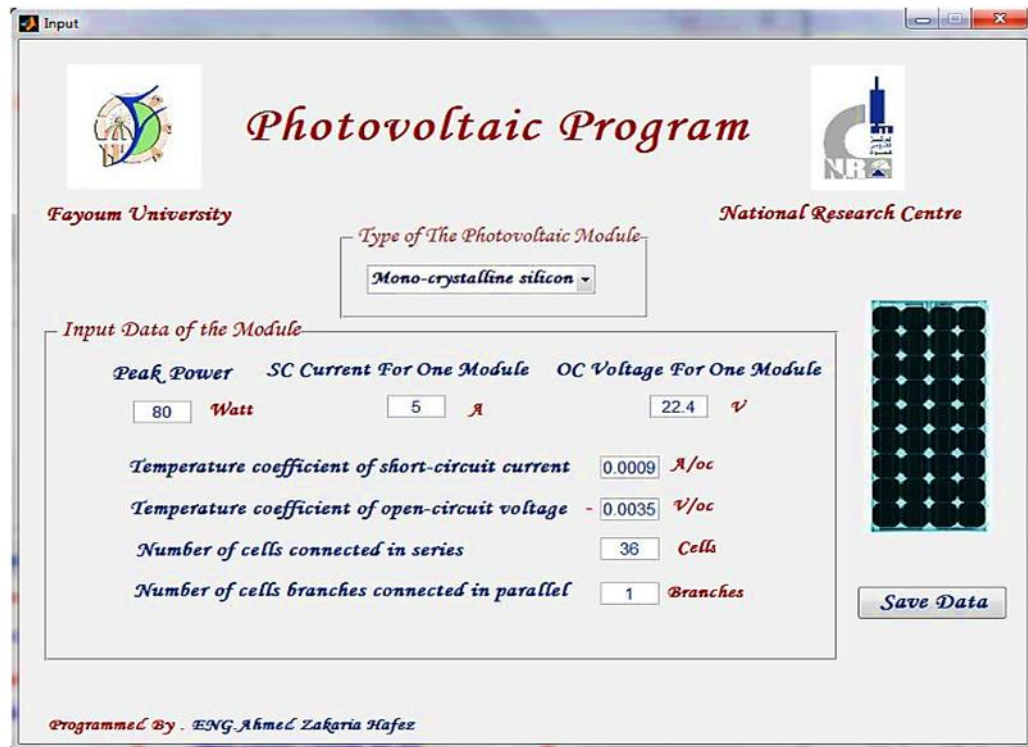


Fig II.9: A figure of the photovoltaic program [42].

N. Belhaouas et al. (2013) developed a Matlab/Simulink-based GUI simulator for modeling PV cells and modules using the two-diode model, offering improved accuracy over the single-diode approach. Key parameters are extracted from datasheet data via the Newton-Raphson method, and the tool generates (I-V) and (P-V) curves under varying temperature and irradiance conditions. It also handles partial shading scenarios by simulating bypass and blocking diode effects on multi-peak power behavior, with validation against commercial modules confirming its reliability [43].

S.V. Spataru et al. (2012) presented a MATLAB-based GUI developed for teaching PV array modelling at Aalborg University. The tool implements three equivalent circuit models; the four-parameter single-diode simple model, the five-parameter single-diode detailed model, and the seven-parameter double-diode model, enabling accuracy and complexity comparisons. The four-parameter model was retained for its analytical parameter extraction directly from datasheet values, avoiding iterative computation. The GUI covers three functional areas: (I-V) and (P-V) curve generation under STC, simulation under variable conditions (irradiance, temperature, partial shading), and parametric analysis. Experimental validation using a flash solar simulator confirmed strong agreement between simulated and measured results [44].

F. Adamo et al. (2011) presented a software tool for PV panel parameterization based on the two-diode equivalent circuit model, focusing on accurate estimation of series and shunt resistances to reliably simulate (I-V) and (P-V) characteristics. A notable feature is the incorporation of irradiance and temperature measurement uncertainties, enabling robust probabilistic parameter estimation. The tool combines MATLAB for solving nonlinear equations via Newton-Raphson iterations with a LabVIEW GUI for data acquisition and visualization. It supports PV array simulation in customizable configurations and demonstrates reliable maximum power prediction, making it a practical tool for feasibility analysis and system design [45].

Table II.1: comparative analysis of previous studies related to PV system modeling , simulation and sizing

Writer	Method	Advantages	Challenges
Abdularzzaq and all (2025)	Hybrid GA-PSO for SDM parameter extraction	High accuracy ,fast convergence, reduced computational cost	Requires optimization algorithms and higher implementation complexity
Nfaoui and all (2024)	MATLAB/Simulink single-Diode Model with wind speed integration	High prediction accuracy , considers irradiance , temperature and wind speed	More meteorological data required for accurate simulation
Nordin and all (2020)	MATLAB GUIDE GUI For PV sizing	User-friendly reliable sizing results , simplifies PV design calculations	Limited to predefined sizing assumptions and parameters
Alsdı &Khatib (2018)	Review of PV sizing methods for SAPV and GCPV systems	Comprehensive sinzing methodology , optimization software support, reduced manual calculations	Depends on accurate PV and battery models
Eteiba and all (2013)	MATLAB/GUI simulation and monitoring model using Newton-Raphson	Real-time monitoring , considers irradiance and temperature effects, accurate performance prediction	Computation required

Belhaouas and all (2013)	MATLAB/ Simulink GUI based on the two-Diode Model	High accuracy partial shading analysis , I-V and P-V curve generation	Increased model complexity and parameter estimation effort
Spataru and all (2012)	MATLAB GUI implementing 4,5 and 7 parameter PV models	Educational and comparative platform , flexible modeling	Simplified models may reduce accuracy
Adamo and all (2011)	MATLAB/Lab VIEW tool based on the Two-Diode Model and Newton Raphson	Considers measurement uncertainty, accurate parameter estimation , reliable MPP prediction	Requires iterative calculation and multiple software environments

II.6 Sizing of PV generator

The performance of a photovoltaic generator; and consequently, the entire system is strongly governed by solar irradiance and meteorological variables such as ambient temperature, making their thorough analysis essential for accurate sizing optimization. Moreover, the choice of PV system model significantly influences sizing outcomes, as it directly determines how accurately system performance is predicted, and therefore how reliably the sizing meets the required standards.

II.6.1 PV generator sizing method

In general, the most common optimization methodology that is followed by the researchers starts by defining a specific system size, and then a time series data for solar energy, and ambient temperature. Then based on the nature of the PV system (stand alone, grid, or hybrid), the calculation of system energy source (PV array battery, wind turbine, diesel generator) optimum capacity is done based on system availability index. However, a PV system must be designed to meet the desired load demand at a defined level of security. Many sizing works for PV system can be found in the literature. There are three major PV system sizing

procedures, namely, intuitive, numerical (simulation based), and analytical methods, in addition to some individual methods [37].

II.6.1.1 The intuitive method

The intuitive method is defined as a simplified calculation of the size of the system carried out without establishing any relationship between the different subsystems or taking into account the random nature of solar radiation, so it involves estimating the daily load demand, optimizing the tilt angle, calculating the size of the PV array, This method can be based on the lowest monthly average of solar energy (worst month method) or the average annual or monthly solar energy [37].

- Site location and solar potential determination methods:

The first step in sizing a photovoltaic installation is to determine the site location which involves defining the geographic position of the photovoltaic system installation by specifying its coordinates; namely: latitude, longitude, and altitude, and then a time series data of solar energy, ambient temperature along with any supplementary information pertaining to the site where relevant.

- The lowest monthly average of solar energy (worst month method):

In this method, the recoverable energy is estimated over a critical period of one month, referred to as the most unfavorable month. This month corresponds to the period during which the average monthly irradiation value is at its lowest throughout the year, or in certain countries, the period during which winter conditions are most severe.

- The average annual:

This method closely resembles that of the most unfavorable month. It likewise utilizes daily irradiation expressed in kWh/m²/day, over a period of one year.

- The solar equivalent hours (Peak Sun Hours):

Solar irradiance varies continuously throughout the day: it rises from zero at sunrise, peaks around solar noon, and returns to zero at sunset. Rather than working with this continuously fluctuating curve, which would complicate calculations considerably, the PSH concept only takes the number of hours during which the sun would shine at its standard reference intensity of 1000 W/m².

- Calculation of the energy requirement of an autonomous installation:

The estimation of electricity consumption, and knowledge of the periodicity of its needs, where the average total daily energy required (E_{cj} , Wh/day) is the sum of the energy consumption of the various devices that make up the system under study, namely televisions, lamps, electronic devices, etc.

$$E_{Tot} = \sum P_i * t \quad (II.27)$$

Where:

E_{Tot} is the total daily energy consumption in (Wh).

P_i is the consumed power by the load in (W).

T is the daily time of use in (h).

- Sizing of the photovoltaic generator:

To define the size of the PV generator, mainly means the calculation of the total number of modules needed to feed the load.

➤ The peak power of the generator P_c to feed the load:

$$P_c = \frac{G_r * E_{tot}}{G * FCG} \quad (II.28)$$

Where: FCG is the global correction/loss factor.

➤ The total number of modules N_{Tot} :

$$N_{Tot} = \frac{E_{Tot}}{\eta_M * G * S_M * FCG} \quad (II.29)$$

Where:

η_M is the efficiency of the PV module.

S_M is the surface of the PV module in (m²).

➤ Or in function of the peak power of load and module:

$$N_{Tot} = \frac{P_c}{P_{CM}} \quad (II.30)$$

With:

$$P_c = G_r * S_M * \eta_M \quad (II.31)$$

Where: P_{CM} is the peak power of the used PV module.

Based on this method, the required PV modules capacity can be calculated using the formula as follows:

$$P_{PV} = \frac{E_{Tot}}{\eta_s * \eta_{inv} * PSH} * Sf \quad (II.32)$$

Where:

PSH is the number of peak sun hours; when solar radiation equals to (1000 W/m²).

η_s and η_{inv} are the efficiencies of the system components.

Sf is the safety factor that represents the compensation of resistive losses and PV-cell temperature losses.

➤ Number of strings in series:

$$N_s = \frac{V_{bus}}{V_M} \quad (II.33)$$

Where:

V_{bus} is the system bus voltage, or inverter input.

V_M is the nominal voltage of one module (usually V_{mp} from datasheet).

➤ Number of strings in parallel:

$$N_p = \frac{I_{bus}}{I_M} \quad (II.34)$$

Where:

I_{bus} is the system bus current, or inverter input.

I_M is the nominal current of one module (usually I_{mp} from datasheet).

➤ The size of photovoltaic surface:

$$S_{PV} = N_{Tot} * S_M \quad (II.35)$$

➤ The choice of nominal operating voltage of photovoltaic field:

In stand-alone systems, for a given power level, a low voltage implies high currents, which in turn produce ohmic losses in the cables. The operating voltage is chosen according to the peak power of the photovoltaic array in watts; as a general rule, the following table provides the most appropriate voltage for each power range of the photovoltaic array.

Table II.2: The operating voltage of photovoltaic systems according to their peak power.

Power of Photovoltaic field	0 – 500Wc	500Wc –2kWc	2 -10 kWc	>10 kWc
Recommended tension	12V	24V	48V	>48V

This method is a quick technique for approximating or validating the side of a PV system. However, the major disadvantage of this method is that it may cause an over/under-

sizing of the designed system, which results in a low reliability of the system or high cost of energy produced. Consequently, it can be combined with other methods.

II.6.1.2 The numerical method

On the other hand, in numerical method, a system simulation is used. For each time period considered, usually a day or an hour, the energy balance of the system and the battery load state are calculated. These methods offer the advantage of being more accurate, and the concept of energy reliability can be applied in a quantitative manner. System reliability is defined as the load percentage satisfied by the PV system for long periods of time. These methods allow optimizing the energy and economic cost of the system. However, these methods can be divided into two types, namely, stochastic and deterministic. In the stochastic methods, the author considers the uncertainty in solar radiation and load demand variation by simulating an hourly solar radiation data and load demand. Meanwhile, the deterministic method is represented by using of daily average of solar energy and load demand due to the difficulties in finding hourly solar energy available data set [37].

II.6.1.3 The analytical method

In the case of analytical method, equations describe the size of the PV system as a function of the reliability are developed. The main advantage of this method is that the calculation of the PV system size is very simple, while the disadvantage of this method is represented by the difficulty of finding the coefficients of these equations and that these equations are location- dependent factors [37].

II.7 Conclusion

This chapter has examined the mathematical and electrical models of photovoltaic cells and modules, has analyzed the key electrical characteristics affecting solar system performance. It also has reviewed previous studies that have contributed to the development of photovoltaic system modeling and simulation techniques, leading to improved efficiency.

These studies have demonstrated the importance of modeling and simulation in understanding the behavior of solar cells under varying operating conditions, as well as their role in optimizing photovoltaic system design and determining dimensions effectively. Furthermore, the chapter has presented methods for connecting solar cells and techniques for sizing photovoltaic generators to meet specific energy consumption requirements.

The theoretical and mathematical knowledge presented in this chapter has allowed for a better understanding of the behavior of photovoltaic systems, and has formed an important basis for moving on to the practical side and simulation that has been addressed in the chapter three.

Chapter III

Design and Implementation of a **MATLAB Graphical Interface for** **PV Generator Sizing**

General

Conclusion

General Conclusion

The design and sizing of PV systems, and specifically PV generators represent a complex and time-consuming process, requiring a thorough understanding of multiple interdependent components; from solar radiation assessment and load profiling to the modeling of PV modules, and other units, Traditionally, this process have been carried out through lengthy manual calculations or scattered computational tools, making it inaccessible and error-prone, particularly for students and early-stage researchers entering the field. The need for a unified, reliable, and easy-to-use tool capable of streamlining this process was therefore the primary motivation behind this work.

The work presented in this research addressed the analytical sizing and simulation of PV generators, covering both the theoretical foundations and the practical implementation of a dedicated computational tool. The central contribution of this thesis is the development of an interactive graphical interface using MATLAB, designed to assist engineers, students, and researchers in sizing and simulating stand-alone PV generators. The interface integrates the key steps of the analytical sizing process; from solar resource assessment and load estimation to the determination of optimal PV array, battery bank, and inverter configurations, into a unified and accessible environment. By automating these calculations and offering visual simulation outputs, the tool significantly reduces the time and effort required to design reliable off-grid photovoltaic systems.

The results obtained through the interface demonstrated the consistency and validity of the implemented methodology, confirming that the analytical approach provides reliable sizing outcomes when applied under realistic conditions. The tool proved capable of handling the principal parameters influencing system performance, offering a practical and educationally valuable resource for anyone working in the field of renewable energies and PV system design.

Looking ahead, this work opens several promising directions for future development. The interface could be extended to incorporate additional simulation models, optimization algorithms, and economic analysis modules, making it an even more comprehensive design tool. Furthermore, the authors aspire to see this application evolve beyond its current academic scope — potentially becoming a widely adopted software tool used by students, researchers, and practitioners across the renewable energy sector, contributing meaningfully to the advancement of sustainable energy solutions.

List of

References

References

- [1] A. Yahfdhou, A. K. Mahmoud, and I. Youm, 'Evaluation and determination of seven and five parameters of a photovoltaic generator by an iterative method', *SGRE*, vol. 07, no. 09, pp. 247–260, 2016, doi: 10.4236/sgre.2016.79019.
- [2] A. Yahfdhou, A. K. Mahmoud, and I. Youm, 'Evaluation and determination of seven and five parameters of a photovoltaic generator by an iterative method', *arXiv preprint arXiv:1601.03257*, 2016, Accessed: May 20, 2026.
- [3] 'User Guide for PV Dynamic Model Simulation. National... - Google Scholar'. Accessed: May 20, 2026.
- [4] E. GHATAOUI, H. KHELIFI, and A. MENASRIA, 'Alimentation d'un Moteur Asynchrone à partir d'un Générateur Photovoltaïque', PhD Thesis, Université Ahmed Draïa-Adrar, 2019.
- [5] R. Venkateswari and N. Rajasekar, 'Review on parameter estimation techniques of solar photovoltaic systems', *Int Trans Electr Energ Syst*, vol. 31, no. 11, Nov. 2021, doi: 10.1002/2050-7038.13113.
- [6] S. Hoang, 'The environmental history of solar photovoltaic cells', 2017, Accessed: Mar. 04, 2026.
- [7] A. S. Joshi, I. Dincer, and B. V. Reddy, 'Performance analysis of photovoltaic systems: a review', *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 1884–1897, 2009.
- [8] R. A. Marques Lameirinhas, J. P. N. Torres, and J. P. de Melo Cunha, 'A photovoltaic technology review: History, fundamentals and applications', *Energies*, vol. 15, no. 5, p. 1823, 2022.
- [9] S. G. Deshmukh, S. L. Tripathi, and A. Kumar, Eds, *Photovoltaic materials: synthesis, characterizations and applications*. Boca Raton: CRC Press, 2026.
- [10] A. Luque and S. Hegedus, *Handbook of photovoltaic science and engineering*. John Wiley & Sons, 2011. Accessed: Mar. 04, 2026.
- [11] T. Sutikno, H. S. Purnama, R. A. Aprilianto, A. Jusoh, N. S. Widodo, and B. Santosa, 'Modernisation of DC-DC converter topologies for solar energy harvesting applications: A review', *Indones. J. Electr. Eng. Comput. Sci*, vol. 28, no. 3, p. 1845, 2022.
- [12] A. P. Kurian, 'An Investigation into Solar Refrigeration Technology And Its Application To The Indian Agricultural Cold Chain', PhD Thesis, A thesis submitted in partial fulfillment for the requirement of the degree ..., 2012. Accessed: Mar. 04, 2026.
- [13] W. Xu, D. Chen, and H. Qian, 'Non-uniform temperature fields and effects of steel structures: review and outlook', *Applied Sciences*, vol. 10, no. 15, p. 5255, 2020.
- [14] J. Daus, D. Desyatnichenko, and G. Stepanchuk, 'Analysis of Approaches to Determining Solar Radiation Intensity at Preset Geographical Point', in *2020 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)*, May 2020, pp. 1–5. doi: 10.1109/ICIEAM48468.2020.9111932.
- [15] E. Enasel and G. Dumitraşcu, 'Assessment of Polycrystalline, Monocrystalline, and Amorphous Solar Panels Under Dynamic Environmental Conditions: Performance Insights for Renewable Energy Applications', *Bulletin of the Polytechnic Institute of Iaşi. Machine constructions Section*, vol. 70, no. 1, pp. 27–46, Mar. 2024, doi: 10.2478/bipcm-2024-0002.
- [16] 'N° 1846 - Rapport d'information de M. Serge Poignant déposé en ...', Bing. Accessed: Mar. 04, 2026.
- [17] M. Aghaei, S. Damanafshan, M. Abyari, M. Imamzai, M. H. Pourdadash, and Y. H. M. Thayoob, 'An overview of solar cells materials classification', in *Nat Grad 2013. Proceedings of the II National Graduate Conference*, 2014, pp. 18–19. Accessed: Mar.
- [18] 'Polycrystalline 109 • Museum Of Solar Energy', Bing. Accessed: Mar. 04, 2026.

- [19] 'Figure 1.7: Cellule en silicium amorphe[6]', ResearchGate. Accessed: Mar. 04, 2026.
- [20] E. Bailey, 'Types of Solar Panels: A Comprehensive Guide for Buyers', Solar Panel Installation, Mounting, Settings, and Repair. Accessed: Mar. 05, 2026.
- [21] B. Zaidi, 'Introductory Chapter: Introduction to Photovoltaic Effect', in *Solar Panels and Photovoltaic Materials*, IntechOpen, 2018. doi: 10.5772/intechopen.74389.
- [22] W. Abd El-Basit, A. M. Abd El-Maksood, and F. Soliman, 'Mathematical model for photovoltaic cells', *Leonardo Journal of Sciences*, vol. 23, pp. 13–28, 2013.
- [23] P. Sharma and R. K. Mishra, 'Comprehensive study on photovoltaic cell's generation and factors affecting its performance: A Review', *Mater Renew Sustain Energy*, vol. 14, no. 1, p. 21, Apr. 2025, doi: 10.1007/s40243-024-00292-5.
- [24] Q. A. Alabdali, A. M. Bajawi, and A. M. Nahhas, 'Review of recent advances of shading effect on PV solar cells generation', *Sustainable Energy*, vol. 8, no. 1, pp. 1–5, 2020.
- [25] M. Hosenuzzaman, N. A. Rahim, J. Selvaraj, and M. Hasanuzzaman, 'Factors affecting the PV based power generation', in *3rd IET International Conference on Clean Energy and Technology (CEAT) 2014*, IET, 2014, pp. 1–6. Accessed: Mar. 04, 2026
- [26] M. Hosenuzzaman, N. A. Rahim, J. Selvaraj, and M. Hasanuzzaman, 'Factors affecting the PV based power generation', in *3rd IET International Conference on Clean Energy and Technology (CEAT) 2014*, IET, 2014, pp. 1–6. Accessed: Mar. 05, 2026.
- [27] S. Mekhilef, R. Saidur, and M. Kamalisarvestani, 'Effect of dust, humidity and air velocity on efficiency of photovoltaic cells', *Renewable and sustainable energy reviews*, vol. 16, no. 5, pp. 2920–2925, 2012.
- [28] C. M. Tan, B. K. E. Chen, and K. P. Toh, 'Humidity study of a-Si PV cell', *Microelectronics Reliability*, vol. 50, no. 9–11, pp. 1871–1874, 2010.
- [29] A. Abete, E. Barbisio, F. Cane, and P. Demartini, 'Analysis of photovoltaic modules with protection diodes in presence of mismatching', in *IEEE Conference on Photovoltaic Specialists*, May 1990, pp. 1005–1010 vol.2. doi: 10.1109/PVSC.1990.111769.
- [30] K. Ishaque and Z. Salam, 'An improved modeling method to determine the model parameters of photovoltaic (PV) modules using differential evolution (DE)', *Solar energy*, vol. 85, no. 9, pp. 2349–2359, 2011.
- [31] G. M. Masters, *Renewable and efficient electric power systems*. John Wiley & Sons, 2013.
- [32] S. Jenkal *et al.*, 'Development of a photovoltaic characteristics generator based on mathematical models for four PV panel technologies', *Int. J. Electr. Comput. Eng.(IJECE)*, vol. 10, no. 6, pp. 6101–6110, 2020.
- [33] M. G. Villalva, J. R. Gazoli, and E. Ruppert Filho, 'Comprehensive approach to modeling and simulation of photovoltaic arrays', *IEEE Transactions on power electronics*, vol. 24, no. 5, pp. 1198–1208, 2009.
- [34] L. Castaner and S. Silvestre, *Modelling photovoltaic systems using PSpice*. John Wiley and Sons, 2002. Accessed: Mar. 16, 2026
- [35] E. E. Van Dyk, E. L. Meyer, F. J. Vorster, and A. W. R. Leitch, 'Long-term monitoring of photovoltaic devices', *Renewable Energy*, vol. 25, no. 2, pp. 183–197, 2002.
- [36] W. Zhou, H. Yang, and Z. Fang, 'A novel model for photovoltaic array performance prediction', *Applied energy*, vol. 84, no. 12, pp. 1187–1198, 2007.
- [37] T. Khatib and W. Elmenreich, *Modeling of Photovoltaic Systems Using MATLAB: Simplified Green Codes*. John Wiley & Sons, 2016.
- [38] A. K. Abdulrazzaq, G. Bognár, and B. Plesz, 'Enhanced single-diode model parameter extraction method for photovoltaic cells and modules based on integrating genetic algorithm, particle swarm optimization, and comparative objective functions', *J Comput Electron*, vol. 24, no. 2, p. 44, Apr. 2025, doi: 10.1007/s10825-025-02282-w.
- [39] M. Nfaoui *et al.*, 'Comprehensive modeling and simulation of photovoltaic system performance by using matlab/simulink: integrating dynamic meteorological parameters

- for enhanced accuracy', *J.Umm Al-Qura Univ. Appl. Sci.*, vol. 11, no. 3, pp. 633–656, Sep. 2025, doi: 10.1007/s43994-024-00175-5.
- [40] A. S. M. Nordin and A. F. M. Nor, 'Development of Graphical User Interface (GUI) Platform for Sizing a Grid-Connected Photovoltaic (PV) System', *Evolution in Electrical and Electronic Engineering*, vol. 1, no. 1, pp. 15–24, 2020.
 - [41] S. Alsadi and T. Khatib, 'Photovoltaic Power Systems Optimization Research Status: A Review of Criteria, Constrains, Models, Techniques, and Software Tools', *Applied Sciences*, vol. 8, no. 10, p. 1761, Oct. 2018, doi: 10.3390/app8101761.
 - [42] M. B. Eteiba, E. T. El Shenawy, J. H. Shazly, and A. Z. Hafez, 'A photovoltaic (cell, module, array) simulation and monitoring model using matlab?/gui interface', *International Journal of Computer Applications*, vol. 69, no. 6, 2013, Accessed: Apr. 25, 2026.
 - [43] N. Belhaouas, M. S. Ait Cheikh, A. Malek, and C. Larbes, 'Matlab-Simulink of photovoltaic system based on a two-diode model simulator with shaded solar cells', *Revue des Energies Renouvelables*, vol. 16, no. 1, pp. 65–73, 2013.
 - [44] S. Spataru, D. Sera, T. Kerekes, and R. Teodorescu, 'Teaching photovoltaic array modelling and characterization using a graphical user interface and a flash solar simulator', in *Proceedings of the 6th International Workshop on Teaching in Photovoltaics*, Czech Technical University in Czech Republic, 2012, pp. 36–44. Accessed: Apr. 25, 2026.
 - [45] F. Adamo, F. Attivissimo, A. Di Nisio, and M. Spadavecchia, 'Characterization and testing of a tool for photovoltaic panel modeling', *IEEE transactions on instrumentation and measurement*, vol. 60, no. 5, pp. 1613–1622, 2011.
 - [46] 'MATLAB Programming/Graphical User Interface - Wikibooks, open books for an open world'. Accessed: May 24, 2026.