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Titled

Design and economic assessment of a 3 kW photovoltaic grid connected system

Defended in front of the jury composed of:

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Thank

I especially thank Almighty God for the will, health and patience he has given me during all these long years.

I express our deep gratitude to our dear parents for their encouragement, support and sacrifices endured. Of course, I will not forget to thank my dear brothers and sister.

Thus, i would also like to express our sincere thanks to my supervisor Mr. Chouder Aissa first of all for having proposed this theme and who never stopped giving me valuable advice and comments.

Furthermore, i would like to thank all the members of the jury who agreed to judge my work.

I thank all the professors of the Electrical Engineering department, who provided my training throughout study cycle.

Dedication

I would like to dedicate this modest work to

To My dear mother, white heart, the source of inspiration and encouragement, I would like to thank you for your love, your generosity.

To My dear father, the man of my life, my success. Who is always with me. The exemplary father of respect, honesty and love.

To whom God gave me and he blessed me with his love my sister and my brothers (Fatma, Mustapha and Akram)

To the one who loves me as her daughter, my dear aunt

For me. To my strength

To my strength in my weakness, to the perfect friendship, to my friends (Mohamed, Rania, Amira, Khadija...) to everyone who helped me.

Yasmine

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Symbols	Description
PV:	Photovoltaic
kW:	Kilowatt
Km:	Kilometer
W:	Watt
m^2:	Square meters
P-type:	Positive-doped semiconductor
N-type:	Negative-doped semiconductor
P-N:	Diode junction
c-Si:	Monocrystalline Silicon
mc-Si:	Polycrystalline Silicon
a-Si:	Amorphous Silicon
V_{oc}:	Open-Circuit Voltage (V)
I_{sc}:	Short-Circuit Current (A)
FF:	Fill Factor
η:	Efficiency (%)
R_s:	Series Resistance ()
R_{sh}:	Shunt Resistance ()
I-V:	Current Voltage
MPP:	Maximum power point
G:	Irradiance (W/m^2)
T:	Temperature (°K)
°K:	Kelven
DC:	Direct current
AC:	Alternating current
A:	Amps
V:	Volts
L_{DC}:	Lengths of the cable run (m)

I_{DC}:	Current that will flow through the cable (A)
ρ:	Resistivity of the conductor material (Ω.m)
V_{MPP}:	Maximum power point voltage
S:	Cross-section (m)
T_{c-max}:	Maximum operating temperature (T)
T_a:	Ambient temperature (T)
G_{max}:	Maximum solar irradiance (W/m²)
I_{sc-max} :	Effective current (A)
I_{sc-STC}:	Short circuit current module from STC (A)
α_{Isc}:	Short circuit temperature coefficient (% /°C)
I_F:	Fuse current (A)
V_s:	Switch voltage (V)
V_{OC}:	Open circuit voltage from STC (V)
α_{voc}:	Open circuit temperature coefficient (% /°C)
N_p:	Number of solar panel
KA:	Kilo amps
I_D:	Differential circuit breaker current (A)
I_{i-max}:	Max output current of the inverter (A)
NPI:	Net promoter index
APR:	Annual percentage rate
IAM:	Incidence Angle Modifier
STC:	Standard test conditions
NPV:	Net present value
IRR:	Internal rate of return
LCOE:	Levelized cost of energy
DPP:	Discounted payback period
d:	Discount rate (%)
r:	Degradation rate (%)
KWh:	Kilowatt hours

C:	Capacity (kWh)
PF:	Power factor (%)
N_h :	Number of hours per year
E:	Energy
$E_{(n+1)}$:	The energy production for the next year
$E_{(n)}$:	The energy production for the current year
P:	Price (DA)
$P_{(n+1)}$:	Energy price for the next year
$P_{(n)}$:	Energy price for the current year
R:	Revenue (DA)
ANCF:	Annual net cash flow
C_0:	Initial investment (DA)
C_{AV}:	Annual net cash flows (DA)
$C_{O\&M}$:	Operational and maintenance costs
C_E:	Fuel cost
DF:	Discount factor
DCF:	Discount cash flow

Summary

Traditional energy sources like fossil fuels and nuclear power are finite and pose a threat to the environment, necessitating the search for alternative and renewable energy sources. Photovoltaic solar energy is one such promising alternative, enabling the generation of electricity from sunlight using photovoltaic cells through the photovoltaic effect.

Photovoltaic solar power systems are characterized by low operation and maintenance costs, and zero polluting emissions, making them a sustainable and environmentally friendly option. As a result, they are gaining popularity in residential, commercial, and institutional applications.

This work focuses on the design and installation of a 3-kilowatt grid-connected photovoltaic solar power system to power the research laboratories at the Faculty of Technology.

The system comprises a set of interacting components such as solar panels, inverter, cables, switches, fuses, surge protector, and circuit breaker.

Keywords: Photovoltaic solar energy, Grid-connected photovoltaic system, PVsyst, Photovoltaic Inverter, Net present value, Discounted payback period.

Résumé

Les sources d'énergie traditionnelles comme les combustibles fossiles et l'énergie nucléaire sont épuisables et représentent un danger pour l'environnement, ce qui nécessite la recherche de sources d'énergie alternatives et renouvelables. L'énergie solaire photovoltaïque est l'une de ces alternatives prometteuses, permettant de produire de l'électricité à partir des rayons solaires en utilisant des cellules photovoltaïques par effet photovoltaïque.

Les systèmes d'énergie solaire photovoltaïque se distinguent par leurs faibles coûts d'exploitation et d'entretien, et l'absence d'émissions polluantes, ce qui en fait une option durable et respectueuse de l'environnement. C'est pourquoi ils gagnent en popularité dans les applications résidentielles, commerciales et institutionnelles.

Le présent travail porte sur la conception et l'installation d'un système d'énergie solaire photovoltaïque de 3 kilowatts connecté au réseau électrique pour alimenter les laboratoires de recherche de la faculté de technologie.

Le système est composé d'un ensemble de composants interactifs tels que des panneaux solaires, un onduleur, des câbles, des interrupteurs de courant continu et des dispositifs de protection.

Mots clés : Energie solaire photovoltaïque, Système solaire connecté au réseau, PVSyst, Onduleur photovoltaïque, Valeur actuelle nette, Période de récupération actualisée.

ملخص

تُعد مصادر الطاقة التقليدية مثل الوقود الأحفوري والطاقة النووية قابلة للنضوب وتشكل خطرا على البيئة، مما يستدعي البحث عن مصادر طاقة بديلة ومتجددة.

تُعتبر الطاقة الشمسية الكهروضوئية إحدى هذه البدائل الواعدة، حيث تتيح إمكانية توليد الكهرباء من الأشعة الشمسية باستخدام الخلايا الكهروضوئية عن طريق التأثير الكهروضوئي.

تتميز أنظمة الطاقة الشمسية الكهروضوئية بانخفاض تكاليف التشغيل والصيانة، وعدم انبعاث ملوثات، مما يجعلها خيارا مستداما وصديقًا للبيئة. لذلك، تزداد شعبيتها في التطبيقات السكنية والتجارية والمؤسسية على حد سواء.

تمحور هذا العمل حول تصميم وتركيب نظام طاقة شمسية كهروضوئية بقدرة 3 كيلوواط مرتبط بالشبكة الكهربائية لتشغيل مختبرات البحث في كلية التكنولوجيا. يتكون النظام من مجموعة من المكونات المتفاعلة مثل الألواح الشمسية، المحولات، الكابلات، مفاتيح التيار المستمر، وأجهزة الحماية.

الكلمات الدالة: الطاقة الشمسية الكهروضوئية، النظام الكهروضوئي المتصل بالشبكة، المموج الكهروضوئي، صافي القيمة الحالية، فترة الاسترداد المخصومة.

General Introduction

General Introduction

With increasing pressures related to the negative environmental impacts of fossil fuels and the rapid depletion of non-renewable natural resources, it has become imperative to transition towards alternative and sustainable energy sources. Photovoltaic solar energy is one of the most promising technologies in this field, being clean, environmentally friendly, and permanently renewable.

Since Algeria is a sunny country [1], photovoltaic energy was chosen in this study, which is a viable, clean and profitable solution. This technology has already proven itself in many countries. Photovoltaic solar cell technology has witnessed significant development since its discovery in the early twentieth century, which has led to increased efficiency and lower costs this technology can be used in various applications, from small household appliances to power plants. Nowadays, it seems to us that no one can doubt the importance of energy, the demand for energy is increasingly increasing.

The work presented in this thesis concern the design and installation of a 3 kW solar photovoltaic grid connected system to operate LGE laboratory at the faculty of technology at the University of Msila.

To this end, the study presented in this dissertation is organized into four parts. It is summarized as follows:

Before getting to the heart of the matter there is a general introduction.

Chapter one covers the generalities of PV solar energy, including its history and evolution, solar cell and modules, and various applications.

Chapter two addresses the study and design of the grid-connected solar system, including site selection, component sizing, and installation design.

Chapter three presents the simulation of the project using the PVsyst software, where the PV system is modeled, simulated, and the results are analyzed.

Chapter four provides an economic study of the 3 kW on-grid solar projects, including calculation of initial costs, financial analysis, and results discussion.

This thesis aims to highlight to importance of photovoltaic solar energy as an alternative and sustainable energy source and provide a practical solution to meet the electricity needs of the faculty of technology in an environmentally friendly manner. Hope that the results of this project will contribute to promoting the use of solar energy in Algeria and diving sustainable development.

Finally, this work with a general conclusion, which will provide a summary of the work presented.

Chapter I:

Photovoltaic ***Systems: State of the Art***

I.1. Introduction

The sun is an abundant and renewable source of energy that has been harnessed by humans for various purposes throughout history. However, the ability to directly convert solar energy into electricity through the photovoltaic (PV) effect has revolutionized the way we utilize this inexhaustible resource [1].

Photovoltaic technology is based on the principles of solid-state physics and the properties of semiconductor materials, particularly their ability to absorb photons from sunlight and release electrons, generating an electric current. This process, known as the photovoltaic effect, forms the foundation of solar cells, which are the fundamental building blocks of PV systems [2].

In this chapter, the basics of solar photovoltaic will be explored, starting with the photovoltaic effect and the evolution of PV technology.

Next, photovoltaic cells and modules, their working principles, and the various types of PV technologies available will be discussed. This section will also cover the electrical characteristics of solar cells and their performances parameters, which are essential for system design and optimization [3] [4].

Furthermore, the applications of photovoltaic systems will be discussed, ranging from standalone systems to grid-connected installations. The advantages and challenges associated with each application will be explored, providing a comprehensive understanding of the diverse roles that PV technology can play in meeting our energy needs [5].

I.2. Solar energy

Solar radiation is considered the most plentiful and widespread source of renewable energy on planet earth. Estimation suggests that the tremendous amount of energy emitted by the sun and intercepted by the earth within a single hour could sufficiently satisfy the world's total energy needs for an entire year. The sun continually discharges an enormous amount of radiant energy into the solar system; the earth intercepts a very small part of the solar energy radiated into space. An average of 1367 watts reaches each square meters of the outer edge the earth's atmosphere for an average earth-sun distance of 150 million km; this is what we call the solar constant which is equal to 1367 W/m². The portion of energy received on the earth's surface depends on the thickness of the atmosphere to pass through [6].

I.2.1. Solar thermal energy

The term 'solar thermal energy' refers to the energy harnessed from sunlight through glazed solar thermal collector systems, which are used for directly heating water and buildings. The heat concentrated in these collector panels is transferred to a heat transfer fluid.

I.2.1.1. Advantages and disadvantages

- **Advantages**
  - Renewable and clean energy source with zero harmful emissions.
  - After the initial investment, very low operational costs.
  - Can be used for direct heating of water and buildings.
  - Reliable and safe systems that require little maintenance.
- **Disadvantages**
  - High upfront costs for purchasing and installing the panels and systems.
  - Reduced performance in cold or hazy weather conditions.
  - Energy storage for later use is not straightforward.
  - Requires large surface areas of panels to generate significant amounts of energy.

I.2.2. Solar photovoltaic energy

The photovoltaic solar energy process involves directly converting sunlight into electricity through the use of photovoltaic cells. These cells are made from semiconductor materials, most commonly silicon, which generates an electrical charge when exposed to sunlight. The electrical charge created by the solar cells in then captured and channeled as an electrical current that can power electrical devices or be stored in batteries for later use.

In simple terms, photovoltaic technology allows for the direct conversion of sunlight into usable electricity without the need for any intermediate processes. It is a clean, emission-free way to generate electricity from a renewable source.

I.2.2.1. Advantage and disadvantage

- **Advantages**
  - Public acceptance.
  - Suitable for hot countries and remote sites.
  - Relatively low maintenance costs.
  - Non-polluting electrical energy during use.
- **Disadvantages**
  - Still high cost.
  - Relatively low efficiency.
  - Market very limited but developing.
  - Panel lifespan generally limited to 20 years.

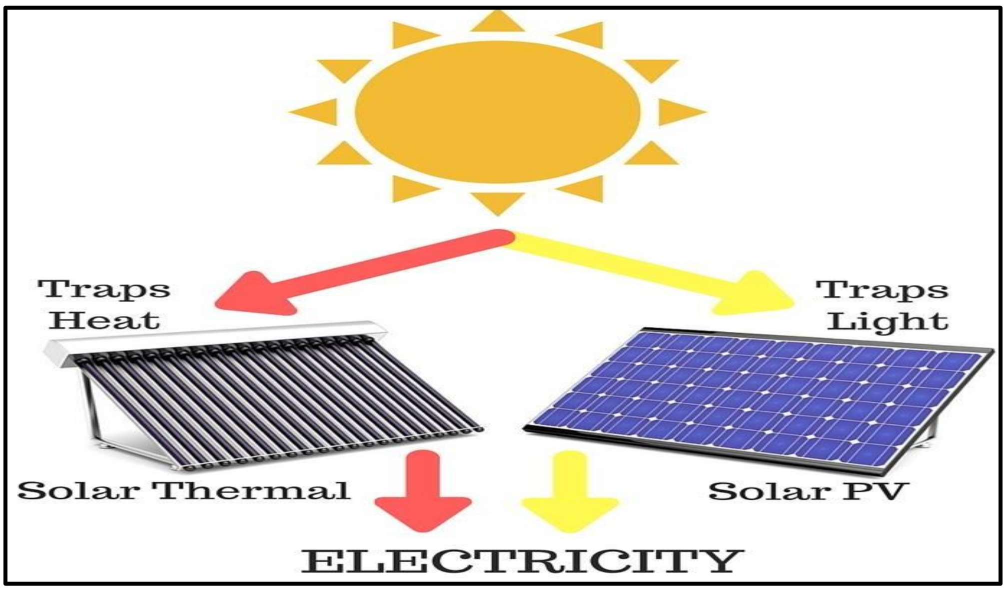

Figure I.1. Types of solar energy

I.3. Photovoltaic effect

The photovoltaic effect is the phenomenon that occurs when light rays fall on a certain surface, imparting their energy to the electrons present in that surface. If the energy of the light rays is sufficient, it will dislodge the electrons from the bonds that bind them to the atoms in the material, leading to their freedom and movement within the material. These free electrons can be utilized to produce an electric current by connecting electrical terminals to the material [7].

This phenomenon is the basis on which solar cells rely in their operation. Solar cells are designed from semiconductor materials such as silicon, in a way that allows the exploitation of the free electrons resulting from the photoelectric effect to produce an electric current.

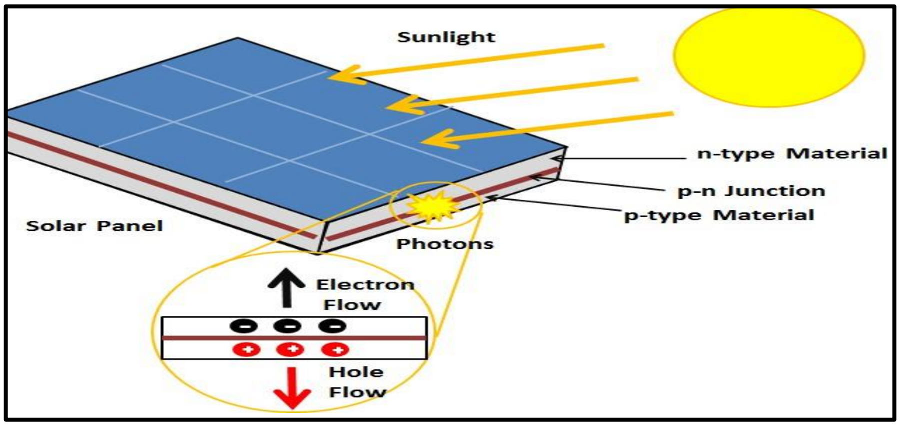

Figure I.2. Photovoltaic effect

I.4. History and evolution of photovoltaic technology

The roots of photovoltaic technology date back to the 19th century when the French scientist Edmond Becquerel discovered the photovoltaic effect in 1839 [8]. Becquerel observed that certain materials produced a small electric current when exposed to light [8].

In 1883, American scientist Charles Fritts developed the first solar cell made of silicon, albeit with a very low efficiency of less than 1% [9].

Little progress was made until the early 20th century when German scientist Adolf Becker developed the first crystalline silicon solar cell in 1941 with an efficiency of around 1% [9].

In 1954, Bell Laboratories in the United States achieved a major breakthrough when scientist Daryl Chapin and Gerald Pearson developed the first crystalline silicon cell with an efficiency of 6% [8].

Since then, PV technology has witnessed rapid advancements, with improvements in efficiency and reductions in manufacturing costs [10]. In the 1970, efforts focused on developing low-cost thin-film solar cells using amorphous silicon (hydrogenated amorphous silicon)[10].

Currently, several PV technologies are competing, such as crystalline silicon cells, thin-film cells, and organic solar cells [11]. Each technology has its own advantages and disadvantages, and over time physicists continue their efforts to improve the efficiency and reduce the costs of each technology.

I.5. The PV cells

I.5.1. Operation of a PV cell

Photovoltaic cells are devices that directly convert light energy into electrical energy through the photovoltaic effect. They consist of two semiconductor layers, one positive (P-type) and one negative (N-type) [12].

When exposed to light, photons are absorbed, causing electrons to be dislodged and leaving holes. Due to the electrical field from the P-N junction, electrons move to the N-layer and holes to the P-layer, generating a voltage difference [12].

I.5.2. Types of cells

There are several main types of photovoltaic cells that differ in their manufacturing materials and characteristics.

I.5.2.1. Monocrystalline Silicon (c-Si) cells: Made from a single continuous crystal of pure molten silicon. They have high efficiency in converting light to electricity, but are more expensive due to the complex manufacturing process.

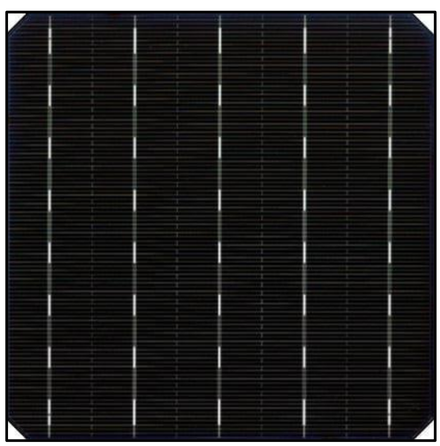

Figure I.3. Monocrystalline cell

I.5.2.2. Polycrystalline Silicon (mc-Si) cells: Composed of multiple small silicon crystals fused together. Less efficient than monocrystalline (c-Si), but cheaper to manufacture.

Figure I.4. Polycrystalline cell

I.5.2.3. Amorphous Silicon (a-Si) cells: Have no distinct crystalline structure. Easy to make as thin inexpensive films, but relatively low efficiency.

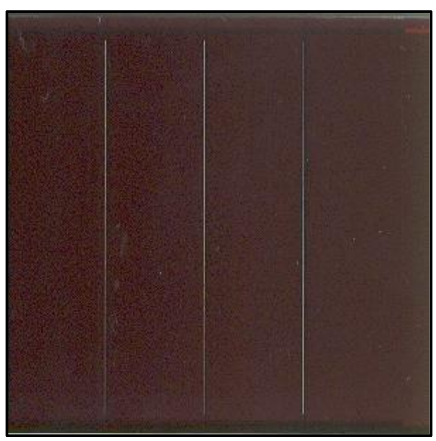

Figure I.5. Amorphous cell

I.6. Electrical characteristics

Solar cells are devices that convert sunlight directly into electricity through the photovoltaic effect. The electrical characteristics of a solar cell are essential in understanding its performance and efficiency. Here are some key electrical characteristics of solar cells:

- **Open-Circuit Voltage (V_{oc}):** This is the maximum voltage that the solar cell can produce when it is not connected to a load. It is determined by the semiconductor material and the design of the solar cell [13], [14].
- **Short-Circuit Current (I_{sc}):** This is the maximum current that a solar cell can deliver when its terminals are shorted, when the voltage across the cell is zero. It is proportional to the incident light intensity and the surface area of the solar cell [13], [14].
- **Fill Factor (FF):** The fill factor is a measure of the maximum power that a solar cell can deliver compared to its theoretical power output ($V_{oc} \times I_{sc}$). It is affected by the series and shunt resistances within the solar cell [13], [14].
- **Efficiency (η):** The efficiency of a solar cell is the ratio of the maximum electrical power output to the incident light power. It is a measure of how effectively the solar cell converts sunlight into electrical energy [13], [14].
- **Series Resistance (R_s):** The series resistance represents the resistance to the flow of current within the solar cell and its external connections. Higher series resistance reduces the fill factor and overall efficiency [13], [14].
- **Shunt Resistance (R_{sh}):** The shunt resistance represents the leakage paths for current across the solar cell, which can be caused by manufacturing defects or impurities. High shunt resistance is desirable for better performance [13], [14].
- **Temperature Coefficient:** Solar cell performance is affected by temperature changes. The temperature coefficients describe how the open-circuit voltage, short-circuit current, and efficiency vary with temperature [15].
- **Current Voltage (I-V) curve:** The I-V curve represents the relationship between the current and voltage output of a solar cell under different load conditions. It provides important information about the cell's performance, such as the maximum power point MPP, where the solar cell operates at its maximum power output [13], [14].

These electrical characteristics are crucial in evaluating and optimizing the performance of solar cells in different applications and operating conditions.

I.6.1. The I-V curve

Figure I.6 illustrates the nonlinear characteristic I-V of a solar cell for an illumination G=1000 W/m² and a temperature T=298°K (conditions of standard operation).

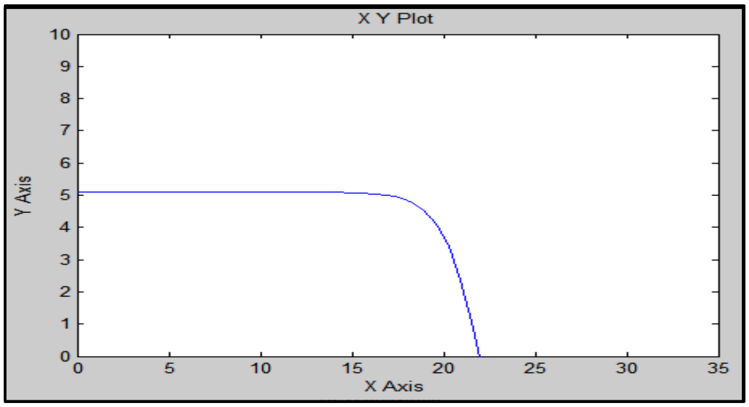

Figure I.6. I-V curve

On the X-axis, voltage is plotted, starting from zero (short circuit) up to the maximum value which is the open-circuit voltage (V_{oc}) when there is no current flow.

On the Y-axis, current is plotted, starting from zero (open circuit) up to the maximum value which is the short-circuit current (I_{sc}) when the voltage is zero.

The point at which the product V*I is maximum is the maximum power point MPP of the cell, which is the ideal operating point.

I.6.1.1. Effect of temperature and solar radiation on the I-V curve

- **Effect of temperature**

Simulation were performed keeping the illumination constant G=1000W/m² for different temperatures 298°K, 323°K, 348°K. The curve of characteristics of solar cell will present different looks depending on the temperature.

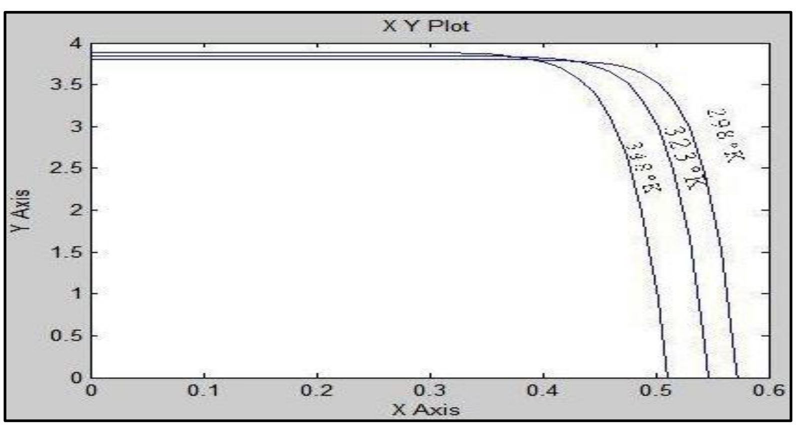

Figure I.7. Influence of temperature on I-V

- An increase in the solar cell temperature leads to a slight decrease in the open-circuit voltage (V_{oc}).
- An increase in temperature slightly increases the short-circuit current (I_{sc}).
- In general, an increase in temperature reduces the power conversion efficiency of the solar cell.

- **Effect of solar irradiance**

Apply a temperature T=298°K kept constant, and varies the radiation G from 400W/m² to 1000W/m², the results obtained are illustrated by the figure following:

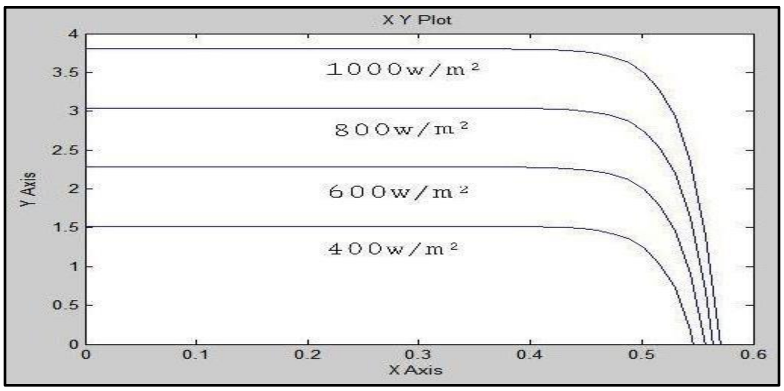

Figure I.8. Influence of solar radiation on I -V

- An increase in the solar irradiance falling on the cell increases the short-circuit current (I_{sc}) proportionally.
- An increase in irradiance does not significantly affect the open-circuit voltage (V_{oc}).
- In general, an increase in irradiance increases the power output and conversion efficiency of the cell.

I.7. The PV module and PV array

In designing a photovoltaic system, it is crucial to determine the required number of modules connected in series and the number of arrays connected in parallel to meet the desired energy demand. Photovoltaic modules are formed by connecting individual solar cells in series. These modules are then assembled in series to create solar panels or strings. The strings are then wired in parallel to form photovoltaic arrays. Finally, multiple arrays can be combined to create utility-scale solar power plants.

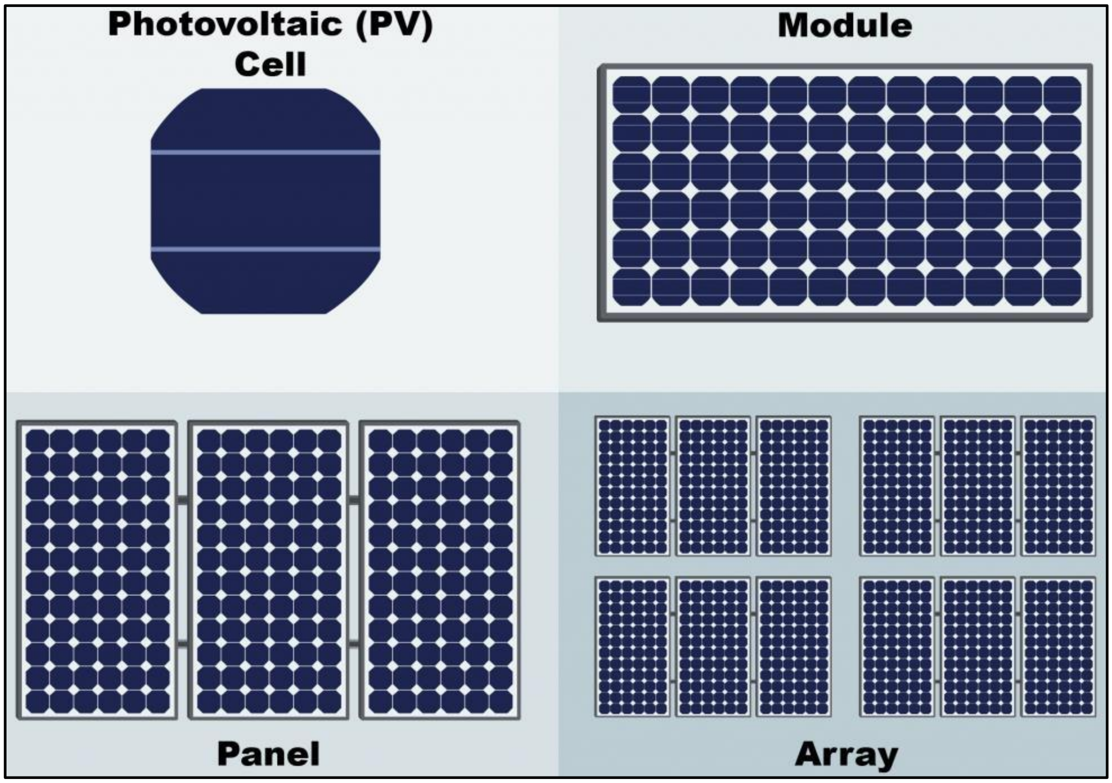

Figure I.9. From cell to array

I.8. Application of solar photovoltaic energy

Photovoltaic systems are classified into two main categories: off-grid (stand-alone) and on-grid (grid-connected) systems. Diesel generators or wind energy can be integrated with off-grid systems to form a hybrid system. The key distinction between the two categories lies in how the produced electrical energy is stored. In off-grid systems, the energy is stored in batteries, whereas in on-grid systems, the excess energy generated is fed into the public utility grid.

I.8.1. Off-grid photovoltaic systems

Stand-alone photovoltaic systems encompass various applications and configuration to provide electricity in remote areas without access to the main utility grid. Two notable examples that fall under this category are solar pumping systems and hybrid renewable systems.

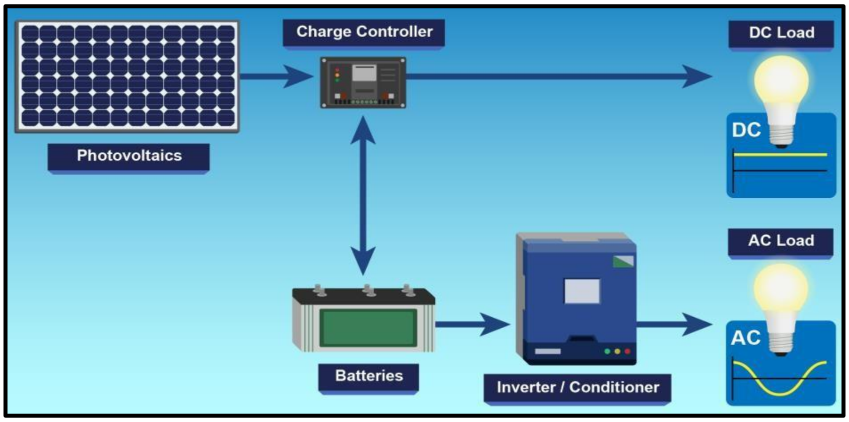

Figure I.10. Stand-alone PV system

I.8.2. Solar Pumping Systems

Solar pumping systems are a specific type of stand-alone solar application where photovoltaic panels are used to power water pumps, extracting water from wells or the other sources for irrigation, livestock, or domestic use in areas lacking grid electricity [16].

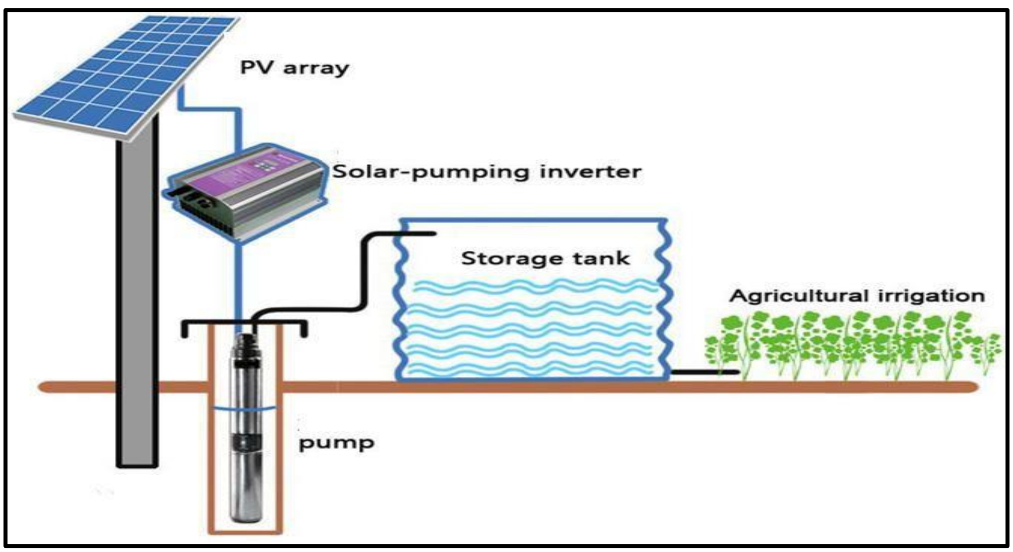

Figure I.11. Solar pumping system

I.8.3. Hybrid Renewable Systems

Hybrid renewable systems, on the other hand, combine multiple renewable energy sources, such as solar panels, wind turbine, and battery storage, to create a more robust and reliable off-grid power system. These systems are particularly useful in areas where a single renewable source may not be sufficient to meet the energy demands consistently [17].

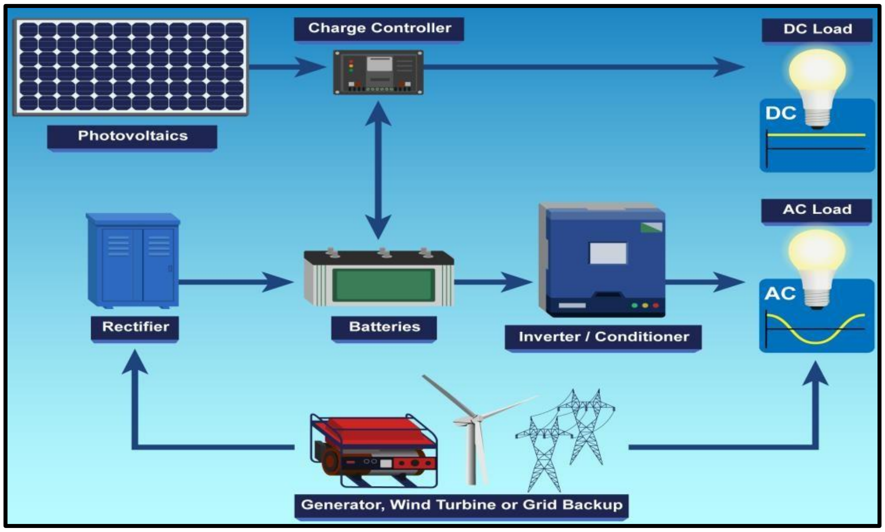

Figure I.12. Hybrid PV system

Both solar pumping and hybrid renewable systems are integral components of the broader off-grid solar ecosystem, providing clean, sustainable, and reliable energy solutions for remote communities, agricultural operations, and other off-grid applications where grid extension is not feasible or cost-effective.

I.8.4. Grid connected photovoltaic systems

Grid connected photovoltaic systems, also known as on-grid photovoltaic systems or utility-interactive PV systems are solar power systems designed to operate while connected to the local utility grid. These systems allow homeowners or businesses to generate their own solar electricity and feed any excess energy back into the grid.

In simpler terms, a grid connected photovoltaic system is a solar power setup that remains liked to the primary electrical grid, enabling a two-way flow of electricity. When the solar panels produce more electricity than the site needs, the surplus is sent to the grid, and when the site requires more power than the solar panels can generate, electricity is drawn from the grid [17].

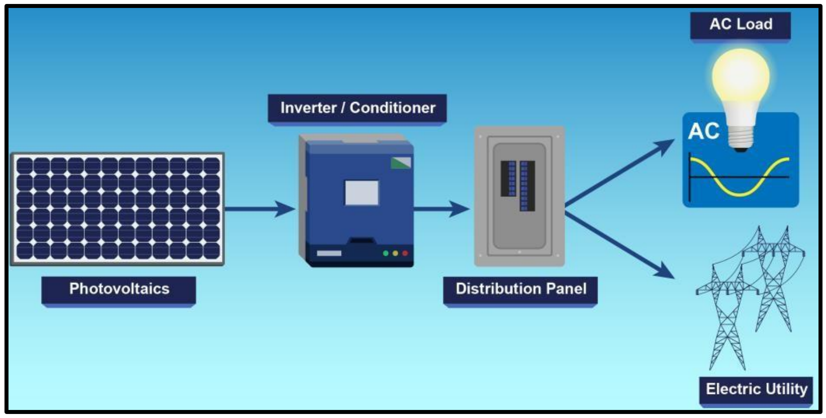

Figure I.13. Grid connected PV system

The following diagram represents the types of solar photovoltaic systems

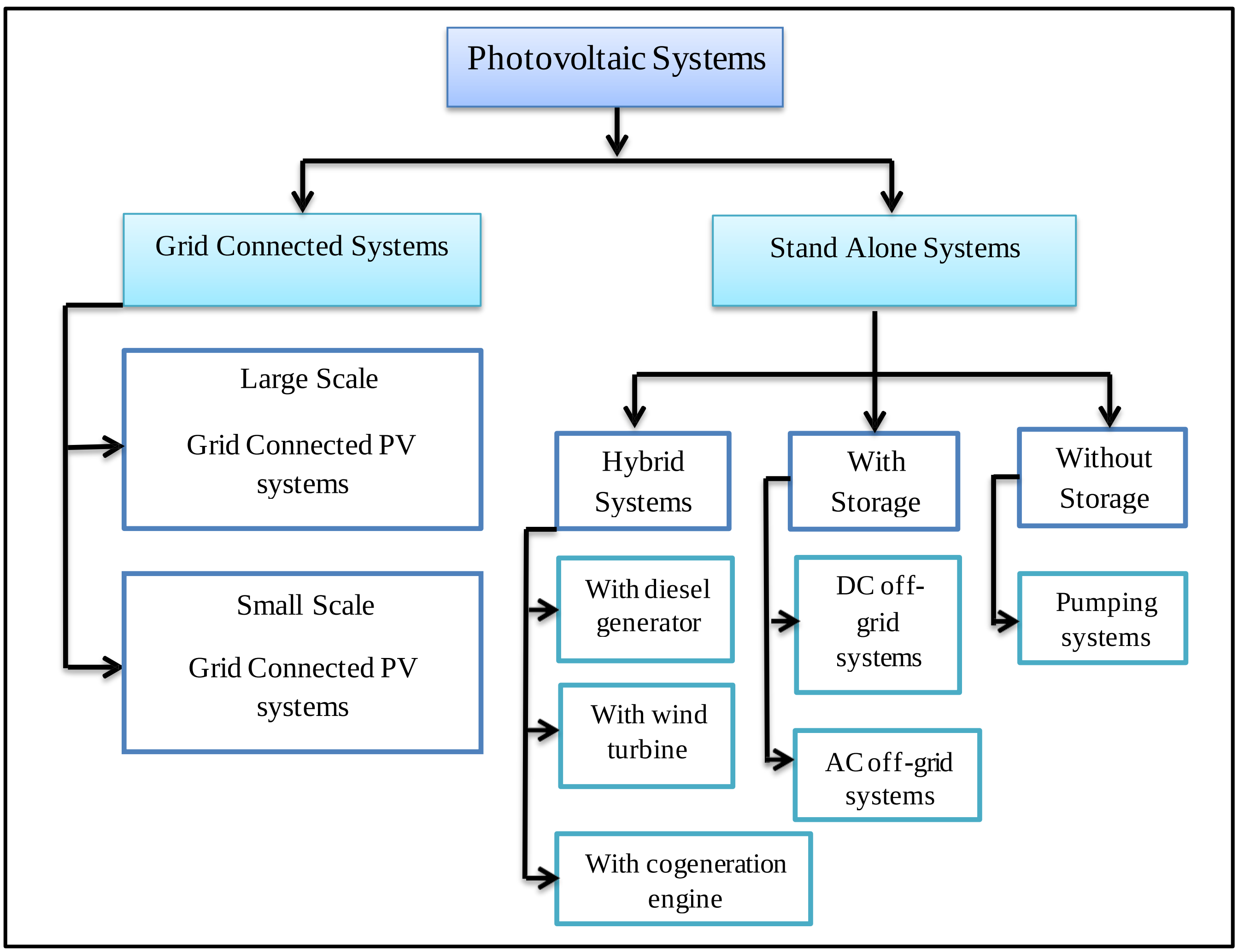

Figure I.14. Photovoltaic systems

I.9. Conclusion

In this chapter, the fundamentals and basic concepts of photovoltaic solar energy were covered. The operating principle of solar cells and the PV effect were discussed, in addition to the advantages, applications, and different types of solar cell technologies. The evolution of solar cell technology throughout history as well as the electrical characteristics of solar modules and arrays was also explored.

The diverse applications of PV solar energy such as stand-alone systems, water pumping systems, hybrid systems, and grid-connected systems were addressed. Despite the challenges and constraints that this technology may face, solar energy remains a sustainable and environmentally-friendly option that is gaining increasing interest.

Through this research, we hope to shed light on the importance of solar energy as a renewable and clean energy source and contribute to promoting its wider adoption in the future.

The next chapter will focus on the design of a grid-connected solar energy system, with detailed calculations for the components of the project I am working on.

Chapter II:

Sizing of a Grid Connected Photovoltaic System: Case study of a 3kWp installed at LGE

II.1. Introduction

This chapter covers grid-connected photovoltaic systems, addressing several important aspects of these systems. It will begin with an overview of grid-connected PV systems and how they operate. Then, it will discuss the site assessment study, which involves evaluating the location in terms of solar potential, environmental conditions, and available infrastructure.

Next, the chapter will delve into the sizing of system components, including solar panels, inverters, cables, and other equipment. It will explain how to calculate electrical loads and determine the appropriate system size.

Finally, the focus will shift to system design and the preparation of engineering diagrams for the proposed installation.

II.2. Presentation of grid-connected PV system

A grid-connected photovoltaic system is a system that generates electricity from solar energy using solar cells, and it is connected to the public electricity grid. This system consists of solar panels that convert sunlight into direct current DC electricity, which is then converted into alternating current AC electricity compatible with the public grid through an inverter [18]. The generated electricity is used to meet the energy needs of the home or building, and any excess electricity is exported to the public grid, while electricity can be imported from the grid when the generated solar power is insufficient [19].

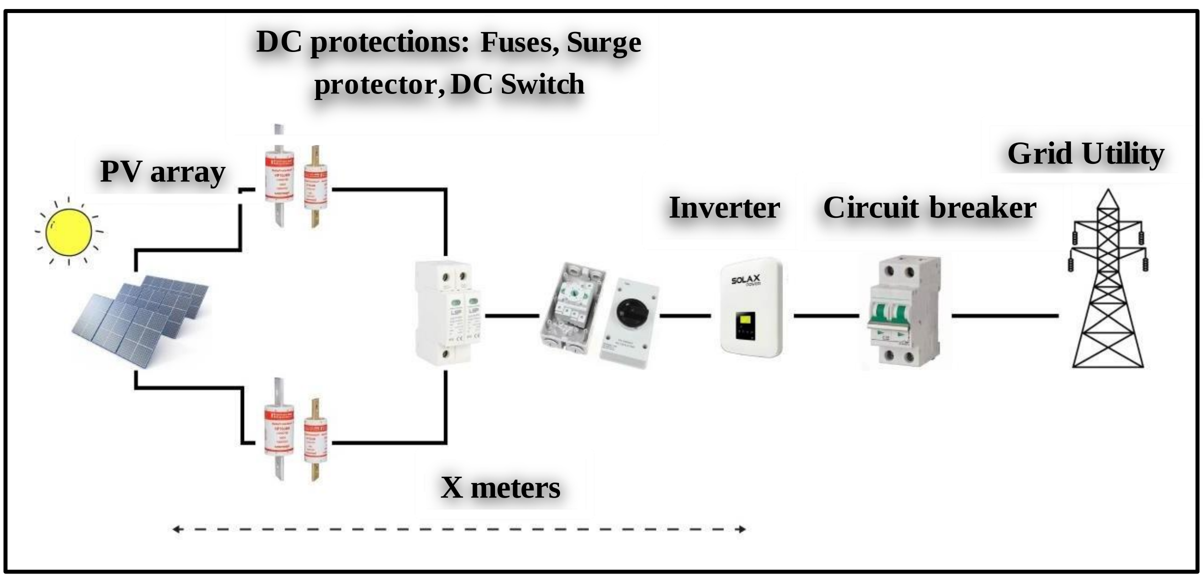

Figure II.1. Grid connected PV system

II.2.1. Main components

Grid-connected photovoltaic systems consist of the following main components:

II.2.1.1. Solar panels: A collection of solar cells that directly convert sunlight into electricity [20].

Figure II.2. Solar panels

II.2.1.1. Inverter: Converts the direct current (DC) output from the solar panels into alternating current (AC) compatible with the public grid [19].

Figure II.3. Inverter

II.2.1.1. Grid-connected system: Connects the system to the public electricity grid and allows for exporting excess electricity or importing electricity when needs [19].

II.2.1.1. Cable: A set of insulated conductors used for transmitting electrical current.

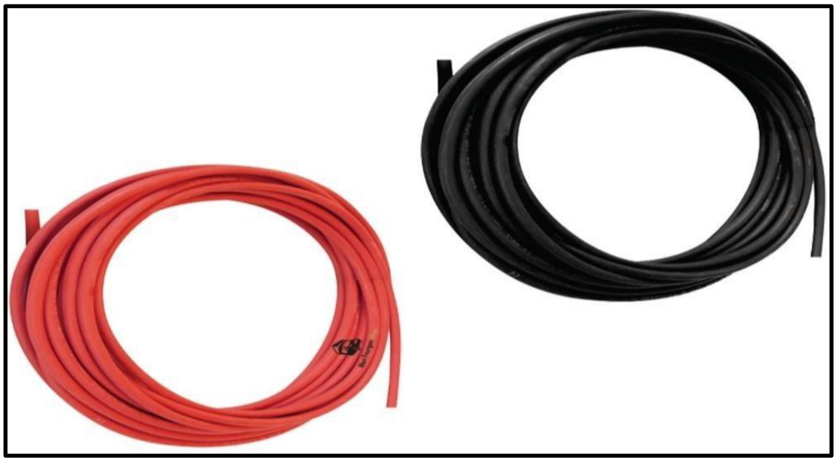

Figure II.4. Solar cables

II.2.1.1. Safety and protection equipment: A group of components intended to protect the system, people and property from potentials risks. This equipment includes the following:

- **Fuses:** Electrical safety devices that melt when the current exceeds the allowed limit, cutting off the electrical circuit to prevent damage.

Figure II.5. Fuses

- **Surge protector:** A protective device installed in an electrical circuit to protect it from high voltages surges caused by lightning or other events.

Figure II.6. Surge protector

- **Switch:** A device that allows manual switching on or off of electrical current in a circuit.

Figure II.7. Switch DC

- **Circuit breaker:** An electrical safety device that automatically disconnects the electrical current when there is an increase in load or a short circuit to prevent damage.

Figure II.8. Circuit breaker

II.3. The standards to consider in the PV system on-grid

Grid-connected photovoltaic systems must comply with various standards and regulations to ensure safety, performance, and grid compatibility.

Some of the most important standards include:

- **Electrical safety standard:** Such as IEC 61730 and relevant local standards to ensure the safety of electrical equipment [21].
- **Component quality standards:** Such as IEC 61215 for solar panels to ensure component quality and efficiency [22].
- **Grid interconnection requirements:** Including standards like IEC 61727 and local utility requirements to ensure system compatibility with the grid [23].
- **Performance standards:** Such as IEC 61853 for measuring system performance and efficiency [24].
- **Local codes and regulations:** Such as building codes and permit/approval requirements for solar projects [25].

II.4. Advantages of grid connected PV system

Grid-connected photovoltaic systems offer several advantages, including:

- Benefiting from the grid simultaneously: Electricity can be imported from the grid when solar production is insufficient, and excess electricity can be exported to the grid.
- No need for battery storage: The generated power is consumed directly or exported to the grid, reducing costs and maintenance requirements.
- Environmental sustainability: These systems contribute to reducing greenhouse gas emissions and promoting the use of renewable energy sources.

II.5. Site Characteristics

Studying the installation site for a photovoltaic system is a crucial step to ensure good performance and a profitable return on investment. In this section, we will analyze the key factors related to the project in the University of Msila.

II.5.1. Meteorological Data

Comprehensive meteorological data from the Meteonorm 8.1 program for Msila region was used for the period from 1991 to 2000. This data includes the following details:

II.5.1.1. Solar Irradiation

Table II.1 represent the solar irradiation values at the project location

Table II.1. Solar irradiation of the location

Annual Global Horizontal Irradiation (kwh/m²)	Annual Diffuse Horizontal Irradiation (kwh/m²)	Global Irradiation on Tilted Panels (33°) (kwh/m²)
1736.5	*707.39*	*1983.4*

II.5.1.2. Temperatures

Table II.2 represent the temperature values at the project location

Table II.2. Temperature of the location

Annual Average Temperature °C	*Highest Monthly Average Temperature °C*	*Lowest Monthly Average Temperature °C*
21.76	*35.28 (July)*	*9.74 (January)*

II.5.2. Plant Location and Orientation

The system is designed with fixed solar panels oriented towards the south azimuth 0° and tilted at an angle of 35°. This tilt angle is generally recommended for areas located around the latitude of 35.7°N like M'sila to optimize the capture of solar radiation throughout the year.

II.5.3. Expected Solar Production

Based on the proposed system configuration, the report estimates an annual solar production of 1620 kwh. It is a good production thanks to the high solar radiation in the Msila region.

Emphasis was placed on the most important key points from the simulation report for the site study.

II.6. Components Sizing

II.6.1. Solar Panels

The solar panel was chosen according to the requirements of the project, and the characteristics of the selected panel are as follows:

The technical characteristics of this photovoltaic panel are on a name plate installed on the back of the PV panel and are also detailed in the PVSYST program as shown in the two figures.

The technical sheet for this photovoltaic panel specifies the following:

- Manufacturer data,
- Electrical properties,

Figure II.9 represent the system definition dialog box when selecting the solar panel, it was taken from PVsyst software.

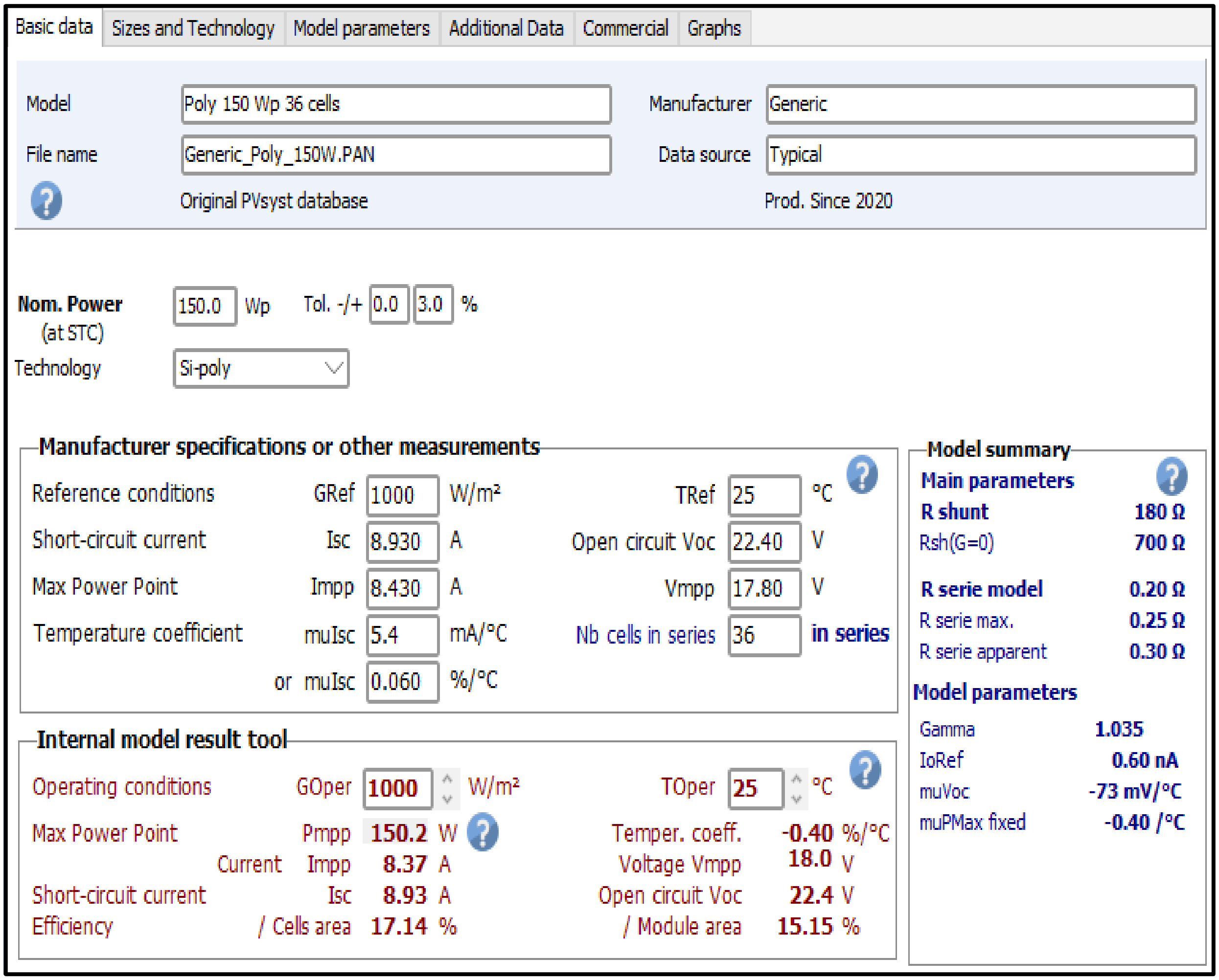

Figure II.9. System definition dialog box when selecting the solar panel

The figure II.10 represent the physical characteristics of the solar panel

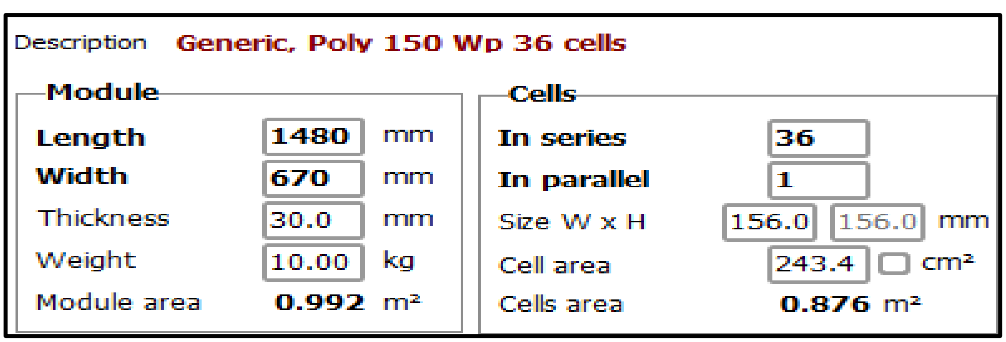

Figure II.10. Physical characteristics of the solar panel

II.6.1.1. Nameplate

Table II.1 represent the characteristics of the photovoltaic panes

Table II.3. Characteristics of the PV panel

Model	Generic, poly 150W 36 cells
Maximum power	150W
Technology	Poly-crystalline
Temperature coefficient	-0.40% / °C
Short-circuit current	8.93A
Open-circuit voltage	22.4 V
Current at(P_{max}) (I_{mpp})	8.37 A
Voltage at (P_{max}) (V_{mpp})	17.80 V
Module efficiency	17.14%

II.6.2. Inverter

The inverter was chosen according to the requirements of our project, which has a capacity of 3 kW, and the characteristics of the chosen inverter are as follows:

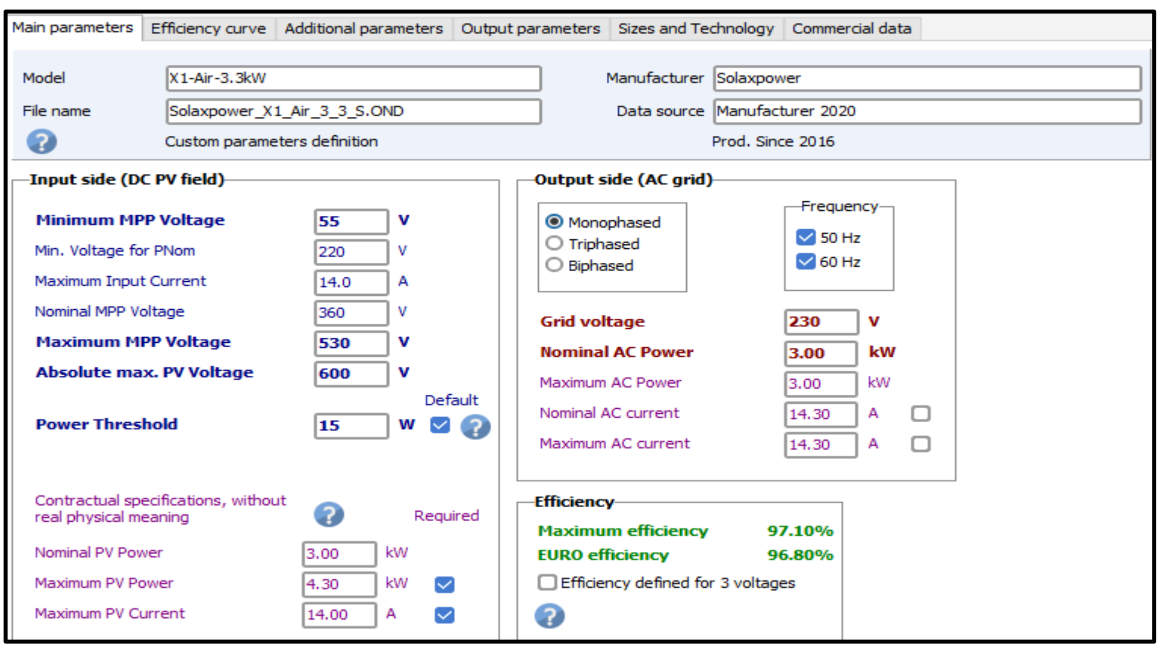

Figure II.11. System definition dialog box when selecting the inverter

II.6.2.1.Technical datasheet

Table II.1 represent the Manufacturer data of the inverter

Table II.4. Manufacturer data of the inverter

Model	Solaxpower X1-Air-3.3kw
Manufacturer	Solaxpower

And the table II.1 represent the information of the input and output parameters of the inverter and also the efficiency.

Table II.5– Input and Output parameters of the inverter

Input parameters DC PV field		***Output parameters AC grid***	
Minimum MPP voltage	*55V*	Grid voltage	*230V*
Min. Voltage for MPP	*220V*	Nominal AC power	*3kw*
Maximum input current	*14A*	Maximum AC power	*3kw*
Nominal MPP voltage	*360V*	Nominal AC current	*14.3A*
Maximum MPP voltage	*530V*	Maximum AC current	
Absolute max.PV voltage	*600V*	***Efficiency***	
Power threshold	*15W*	Maximum efficiency	*97.10%*

II.6.3. Cable Selection

The following equation enables us to calculate the cross-section cables:

$$S = \frac{2 * L_{DC} * I_{DC} * \rho}{Loss * V_{MPP}} \qquad (II.1)$$

Where:

L_{DC}: The lengths of the cable run (m)

I_{DC}: The current that will flow through the cable (A)

ρ: The resistivity of the conductor material

$Loss$: Refers to the allowable or maximum voltage drop over the length of the cable

V_{MPP}: Maximum power point voltage

- **For $\mathbf{V_{MPP} = 55V}$**

$$S = \frac{2 * 100 * 8.43 * 1.7 * 10^{-8}}{0.02 * 55} = 2.6mm^2$$

- **For $\boldsymbol{V_{MPP} = 530V}$**

$$\frac{2 * 100 * 8.43 * 1.7 * 10^{-8}}{0.02 * 530} = 2.7mm^2$$

We take the greatest value, and for more protection we use a greatest cross-section, for example in this project we use $S = 6mm^2$.

II.6.4. Safety and protective equipment

II.6.4.1. DC Side

- **Fuses**

To calculate the fuses, we follow the following steps:

- Calculate the maximum operating temperature of cell.
- Calculate the effective current of the module.
- Finally, we calculate the fuse current.

- **Apply of step:**

- The maximum operating temperature:

$$T_{c\text{-}max} = T_a + 0.03 * G_{max} \qquad \text{(II.2)}$$

$$T_{c-max} = 63.773℃$$

Where:

T_a: Ambient temperature of the location Msila

G_{max}: Maximum solar irradiance at the location

The maximum solar irradiance was obtained from the PVGIS program.

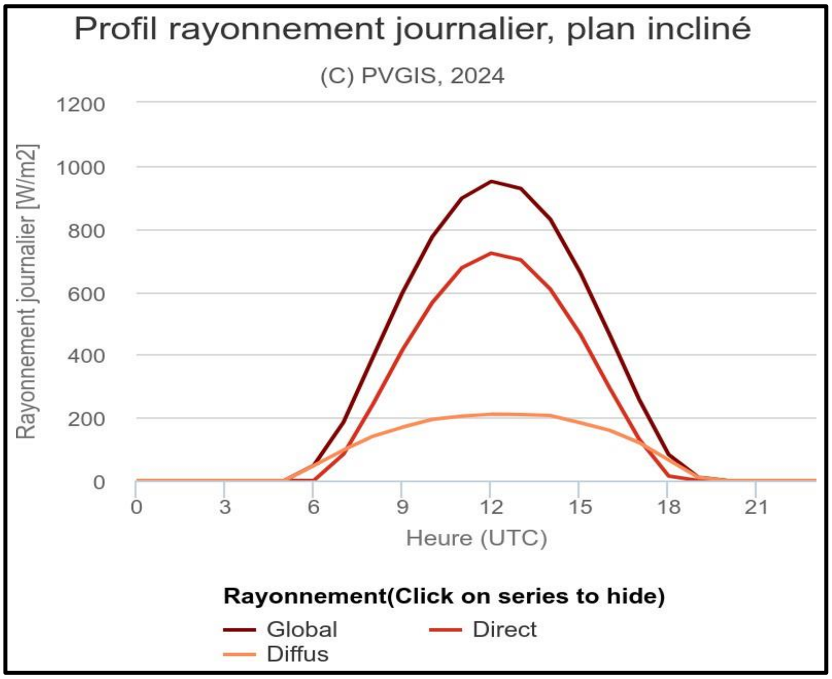

Figure II.12. Solar Irradiance

- **The effective current**

$$I_{(sc\text{-}max)} = I_{(SC\text{-}STC)} *[1+\frac{\alpha_{Isc} * (T_{c\text{-}max} - T_{ref})}{100}] \quad (II.3)$$

$$I_{sc-max} = 8.93 * [1 + \frac{0.06 + (63.773 - 25)}{100}]$$

$$I_{sc-max} = 9.137A$$

Where:

$I_{sc-\mathrm{STC}}$: The short circuit current module from STC

α_{Isc}: Short circuit temperature coefficient

- **The fuse current:** The fuses must be calculated according to the following expression:

$$I_F = 1.25 \times I_{sc\text{-}max} \quad (II.4)$$

$$I_F = 1.25 * 9.137$$

$$I_F = 11.42A$$

A factor of 1.25 is chosen as a safety margin to protect the circuit from any temporary surges in current.

Since a fuse current value of 11.42A was found, we will need a fuse with a larger current value.

So, need two fuses of 16A.

- **DC Switch**

Regarding the Switch DC current, apply the same fuse current equation and find the same result, since the specifications and data used are exactly the same.

And the Voltage,

$$V_s = V_{oc} \times N_p \tag{II.5}$$

- **The effective voltage**

$$V_{max\text{ -eff}} = V_{OC\text{-}STC}\ [1 + \frac{\alpha_{voc}.(T_{C\text{-}Min} - T_{ref})}{100}] \tag{II.6}$$

$$V_{Max-Eff} = 22.4[1 + \frac{-0.4.(9.74-25)}{100}]$$

$V_{Max-Eff} = 23.767V$

$V_s = 23.767 * 20$

$V_s = 475.3V$

Where:

V_{OC} : Open circuit voltage from STC

α_{voc}: Open circuit temperature coefficient

N_p: Number of solar panel

Take DC Switch of 500V, or better yet 1000V.

So the characteristics of the DC Switch are: 16A/1000V.

- **Surge Protector**

As part of designing a 3KW grid-connected PV system, the surge protector DC 1000V, 20KA was selected in accordance with common practices and standards in the small-scale solar power market. This surge protector is considered suitable for providing adequate protection for the DC circuits in a system of this size and capacity. In small projects, key components such as surge arresters are typically chosen based on recommendation from manufacturers and experts in the field, rather than performing complex calculations.

However, the surge protector's specifications were verified to be compatible with the requirements of the designed solar power system, providing a suitable operating voltage of 1000V DC. And a high discharge capacity of 20KA, making it a safe and effective choice for protecting the system against lightning strikes and high electrical surges.

II.6.4.2. AC Side

- **Differential Circuit Breaker**

$$I_D = 1.25 * I_{i\text{-}max} \quad \text{(II.7)}$$

$I_D = 1.25 * 14.3$

$I_D = 17.875A$

Where:

I_D: Differential circuit breaker current

I_{i-max}: Max output current of the inverter

Of standard caliber, choose an AC differential circuit breaker with a current of 25A.

The project we are studying is a small photovoltaic station, so the elements that have been calculated are all we need to install this station.

II.7. Design and diagram of the planned installation

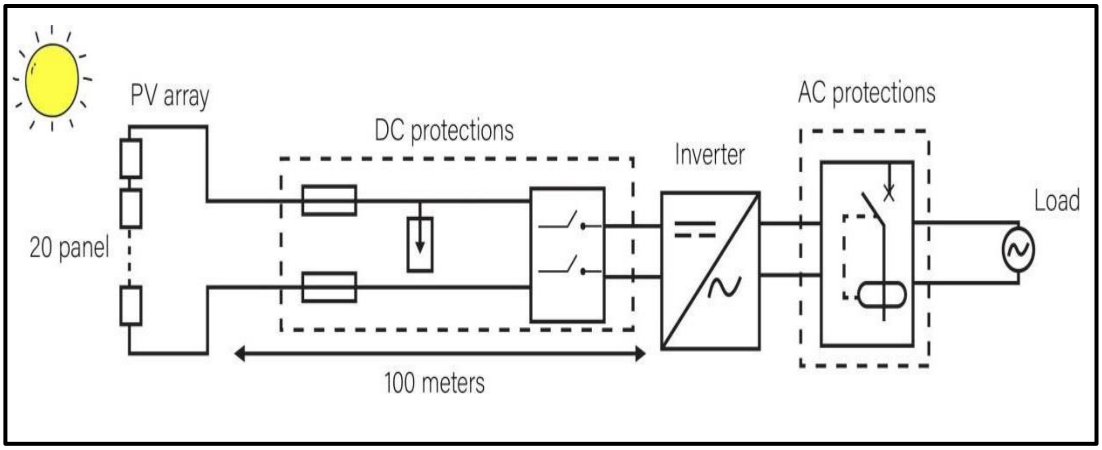

Figure II.13. Station diagram

II.8. Conclusion

In this chapter, PV grid-connected systems are explored in depth. After presenting the main components, operation, and standards governing this type of installation, the numerous advantages it offers are highlighted.

An in-depth study of the installation site was then carried out, taking into account crucial factors such as solar irradiance, optimal orientation, and tilt to maximize energy production.

The detailed sizing of each component was meticulously performed, from the PV panels to the inverter, including wiring, surge protection, and electrical safety devices. These rigorous calculations ensure a safe, efficient, and code-compliant installation.

Finally, a complete schematic of the proposed installation was provided, illustrating the arrangement of the different elements and their interconnections.

The following chapter will tackle the simulation of this system using specialized software, allowing for the analysis of expected performance and further optimization of the design before actual implementation.

Chapter III:

Project Simulation in PVSYST Software

III.1. Introduction

After explaining the theoretical background and photovoltaic technologies in the previous chapters, the focus will now be on the digital simulation aspect of solar photovoltaic systems. Performance simulation is a crucial step in the design and evaluation of any photovoltaic system before its actual implementation.

Specialized simulation software allows of the study of the proposed system's behavior and energy production under a variety of weather and design conditions. Simulation results help make informed decisions regarding technical specifications and identify any necessary modifications or improvements to achieve maximum efficiency.

In this chapter, PVsyst one of the most renowned and widely used solar energy simulation software, will be employed to conduct a simulation study of a grid-connected photovoltaic system. The various steps of the PVsyst simulation will be explained in detail, from preparing input data to analyzing results and proposing potential design improvements.

The main objective is to build and accurate simulation model for the performance of the studies photovoltaic system under specific conditions. This allows for reliable estimation of expected energy production and identification of potential factors that may affect system efficiency. This information will provide a sound basis for making appropriate decisions regarding the final design and feasibility of project implementation.

III.2. Presentation of the PVSYST tool

PVsyst is software of simulating and designing photovoltaic solar power systems, developed by the University of Geneva in Switzerland [27]. Here is a detailed presentation of this tool:

III.2.1. General Description

PVsyst enables the modeling, simulation, and analysis of the performance of grid-connected or stand-alone photovoltaic installation [28]. It takes into account numerous criteria such as local weather date, panel orientation and tilt, potential shading, and component characteristics (modules, inverters, cables, etc.)[27]

III.2.2. Main features

- Sizing of photovoltaic fields.
- Selection and association of components.
- Simulation of energy production.
- Performance and profitability analysis.
- Consideration of near and far shading.
- 3D modeling of the installation.
- Case studies for different scenarios.

III.2.3. Interests and advantages

- Comprehensive tool for design and feasibility assessment.
- Consideration of local weather data.
- Extensive library of photovoltaic components.
- Ability to import your own data[29].
- User-friendly interface.
- Results in the form of detailed reports.

III.3. First contact with PVSYST

When opening PVSYSYT, you access the main page:

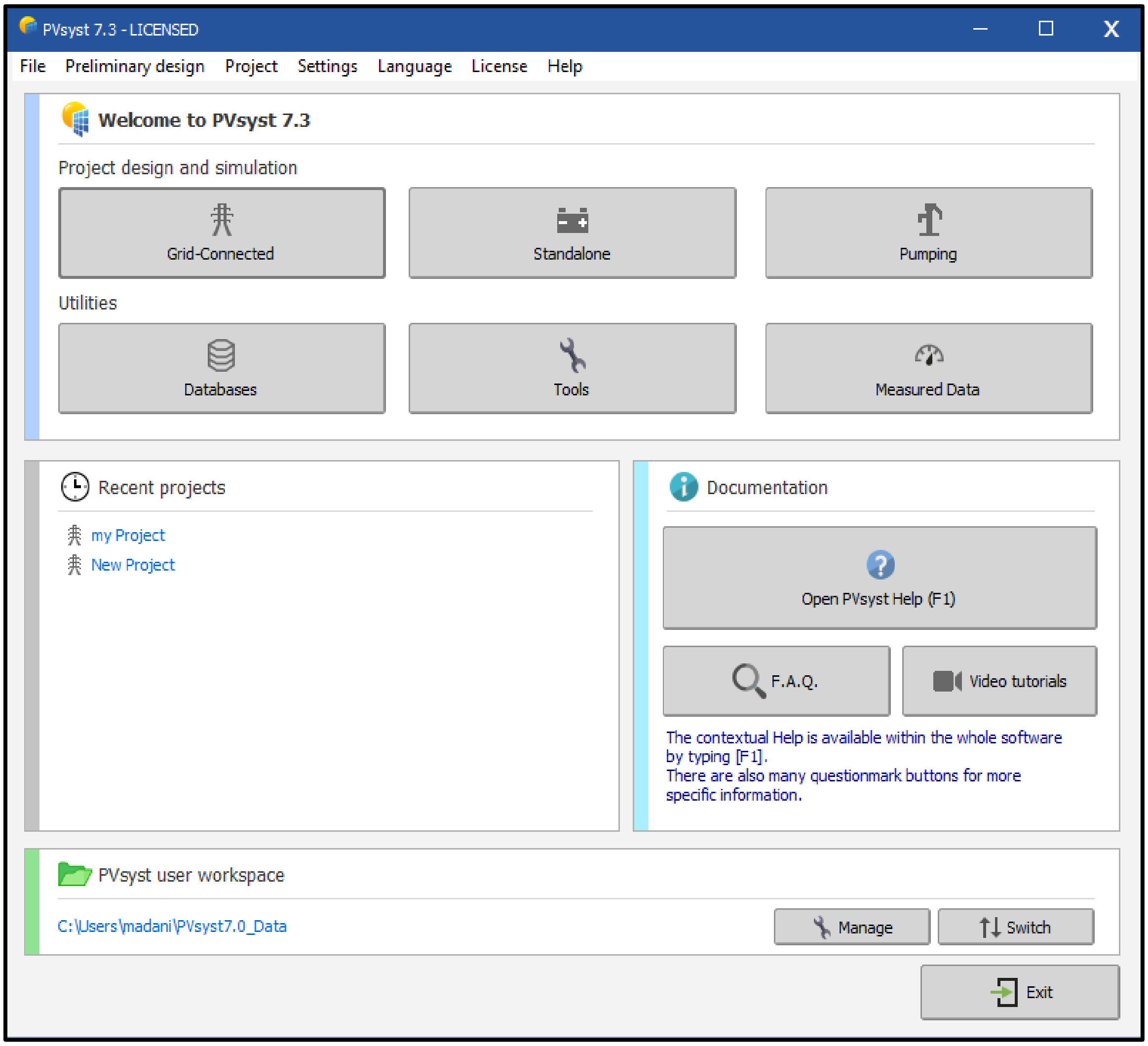

Figure III.1. Pvsyst main page

This gives access to the four main parts of the program:

III.3.1. Project design and simulation

Project design and simulation is the core feature of the software. It is used for the complete study of a project. It involves the choice of meteorological data, system design, shading studies, loss determination and economic evaluation. The simulation is carried out over a full year by time slot and provides a complete report, as well as many additional results.

III.4. Modeling of the PV system

The entire project will be signed and is a networked project. When the project that is connected to the network is selected (figure III.2).

Get a dashboard (figure III.2) to manage the project.

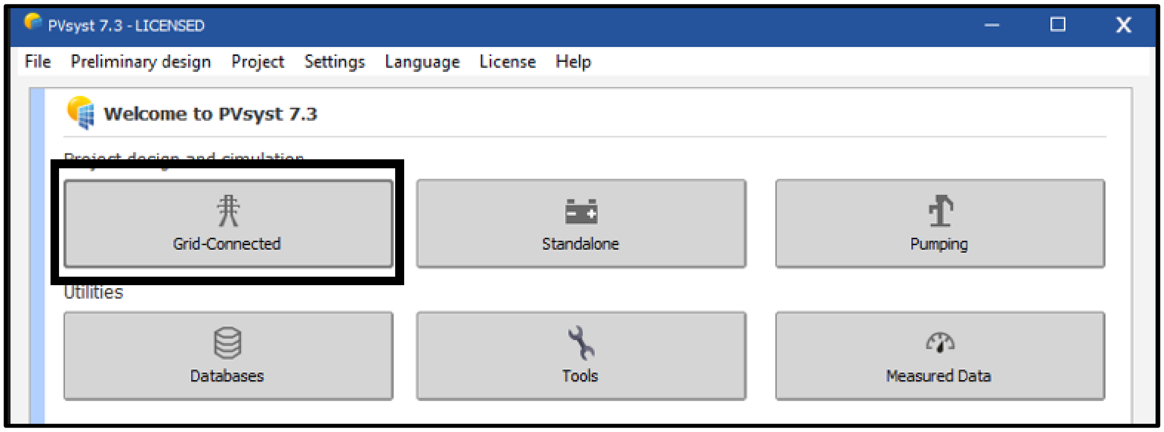

Figure III.2. Start a grid-connected project

This dashboard consists of two parts:

- **Part 1: Project in PVSYST**

The central object upon which various forms of the system are to be build. The project contains the geographic location of the system, a reference to a file containing meteorological data.

- **Part 2: System variables**

Each contains all the detailed definitions of my system, which will trigger the simulation calculation. These definitions include

- Selection of PV panels and reflectors.
- Number of panels and inverters.
- Geometric arrangement and potential shading.
- Electrical connections.
- Different economic scenarios.

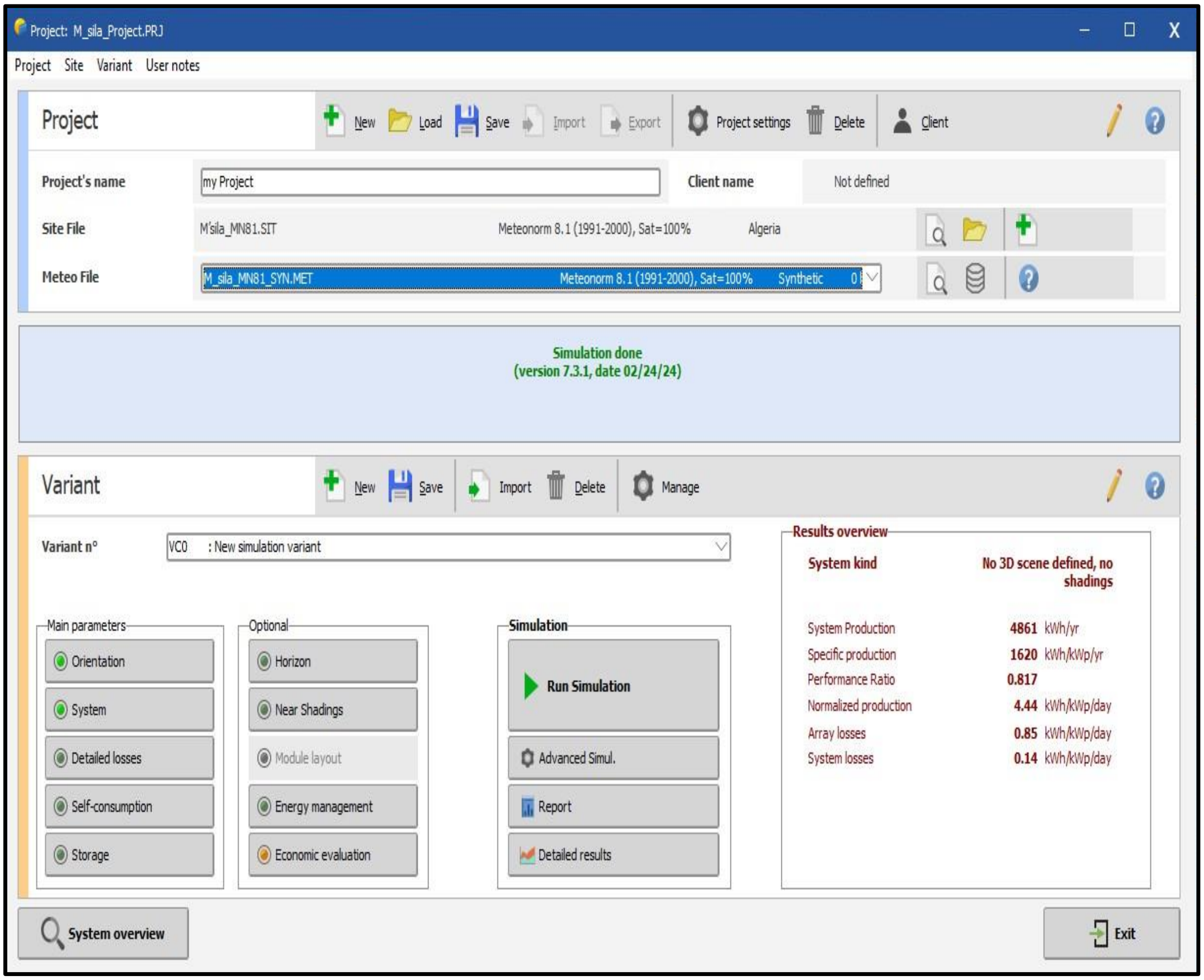

Figure III.3. Project management dashboard

III.4.1. Weather and site data

First, we choose the site through a new site Msila from the site file. Then we select the meteorology file.

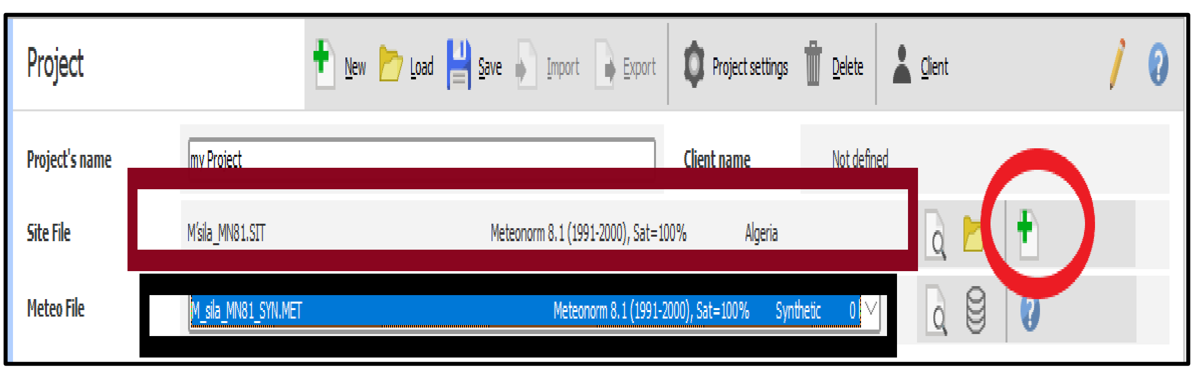

Figure III.4. Choose a geographic site

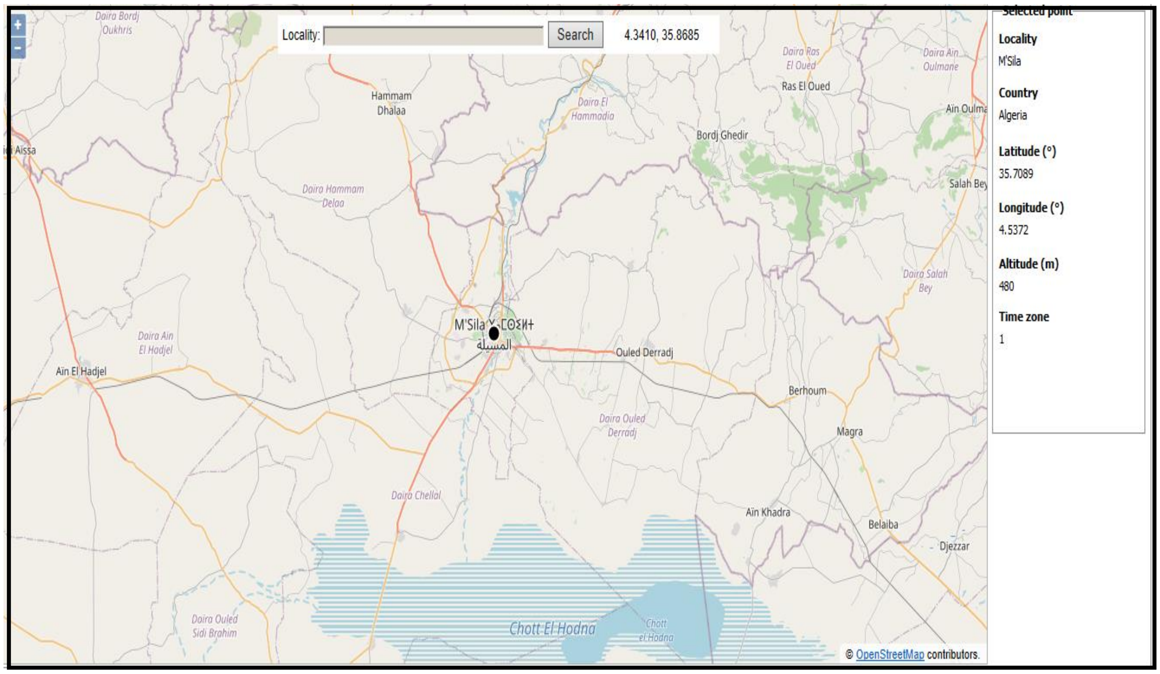

Figure III.5. Interactive project map

III.4.2. Parameters of the chosen components

After we have determined the site and weather data for the project, we move on to determining orientation and system.

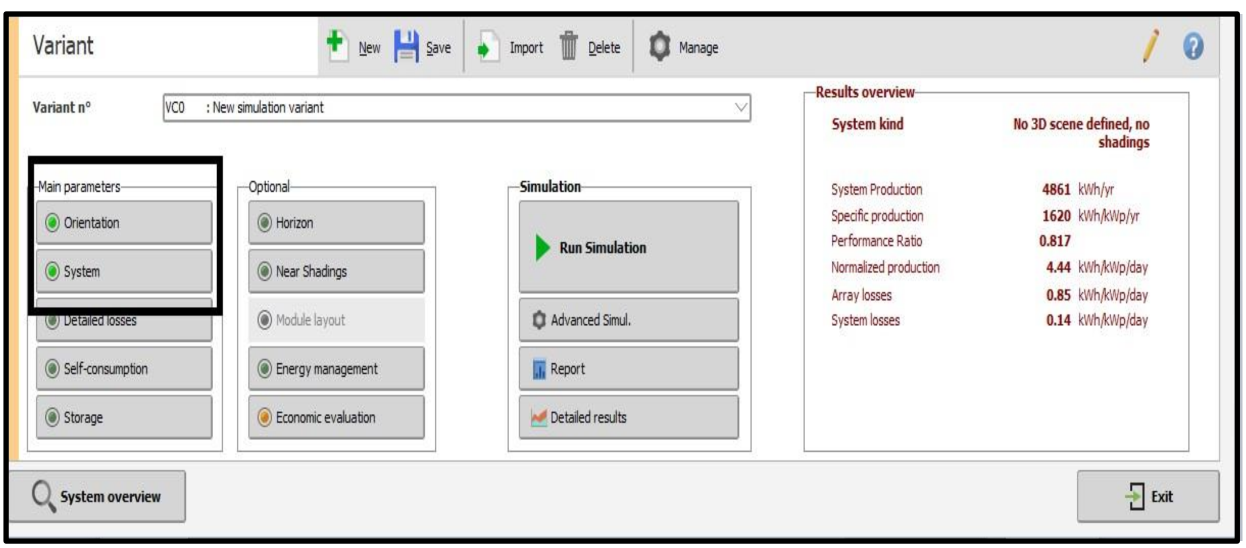

Figure III.6. Two basic parameters orientation and system

III.4.2.1. Orientation

It determines the tilt angle of the solar panels.

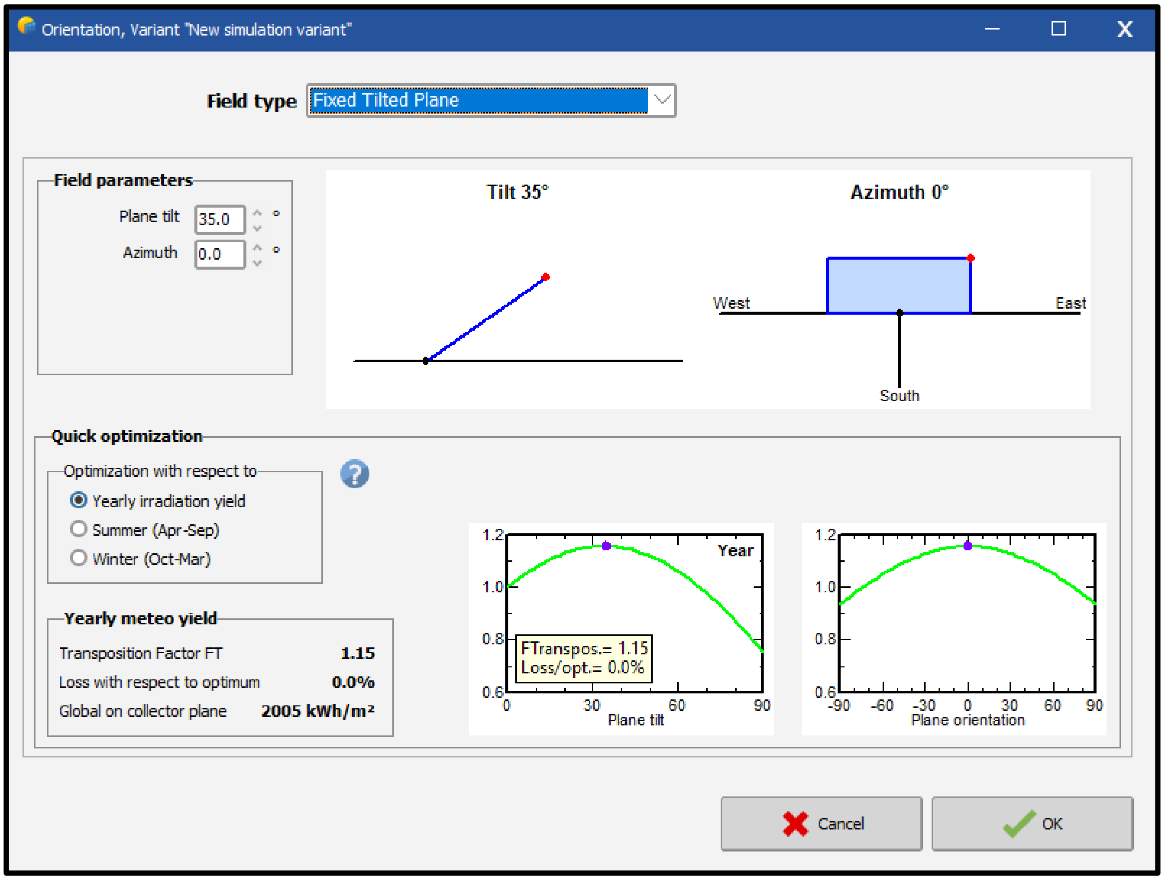

Figure III.7. Orientation dialog

We will install the solar panels on a fixed tiled plane. After setting the correct values for the inclination and azimuth angles (respectively 35° and 0°), we click ok to finish the orientation and head to the system.

III.4.2.2. System

It includes identification:

- Type and number of photovoltaic modules.
- Type and number of inverters used.

- **Select the PV module**

In the previous chapter i determined the capacity and type of solar panel, now we choose it to complete the simulation.

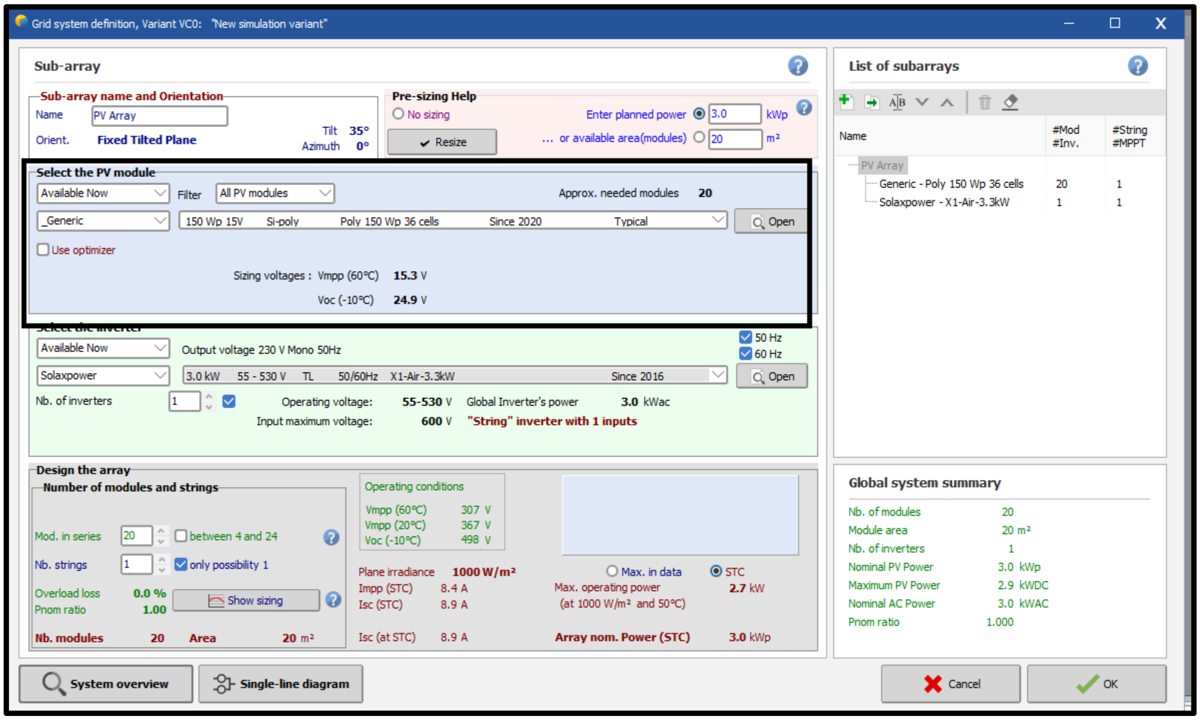

Figure III.8. System definition dialog when selecting PV module

- **Choose an inverter**

Their capacity, type and number were also previously determined. For the installation of our project we chose a 3KW inverter with a single input.

The complete installation configuration for our project also contains: one inverter, one string, containing 20 connected modules.

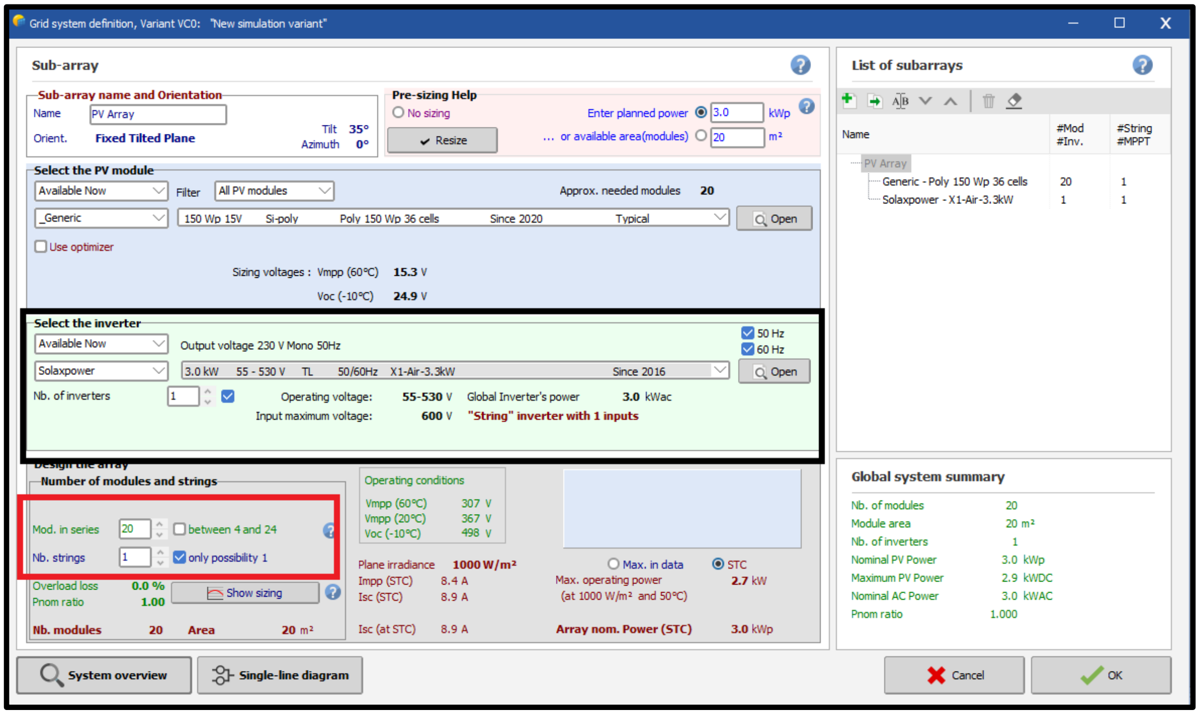

Figure III.9. System definition dialog when selecting inverter

III.4.3. Project simulation

In the project control panel, the start simulation button is activated and we can click on it.

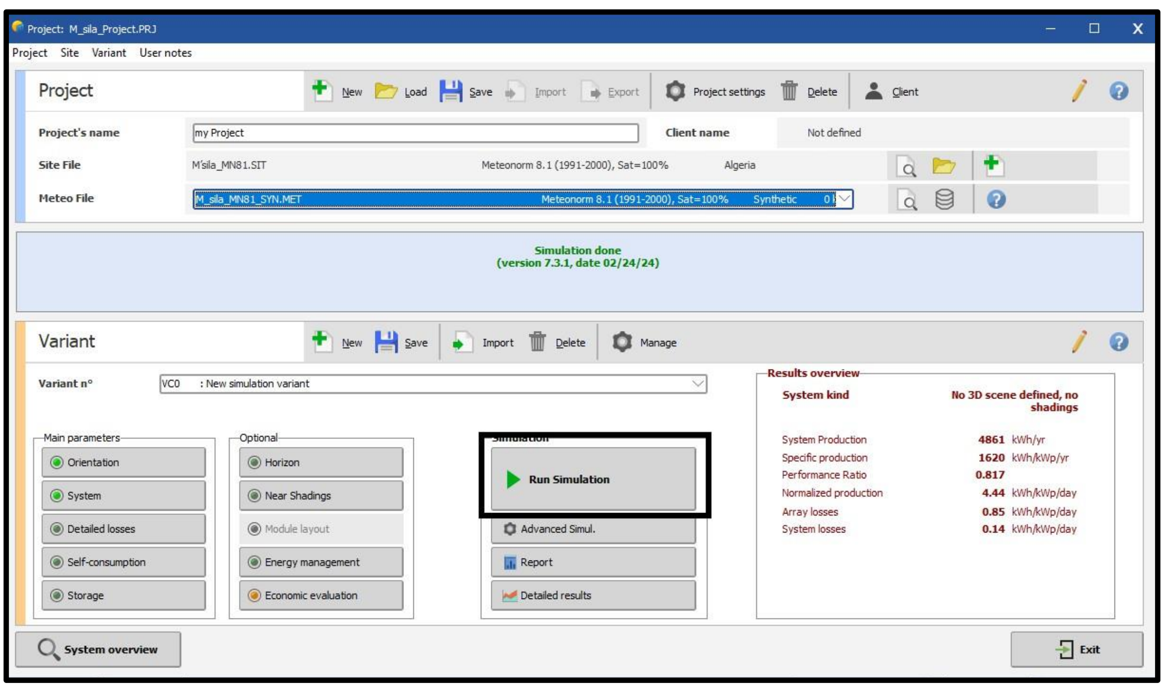

Figure III.10. Simulation run button

III.5. Simulation results

Once the simulation is complete are directed directly to the dialog box containing the results of this project.

III.5.1. Analysis of the results

- This dialog box displays, at the top left, a small summary of the simulation parameters.
- At the top right is a box containing six values summarizing the main results of the simulation, which are approximations of the results.
- At the bottom of the dialog box, several graphs appear that actually provide more detailed information about the overall behavior of the system.

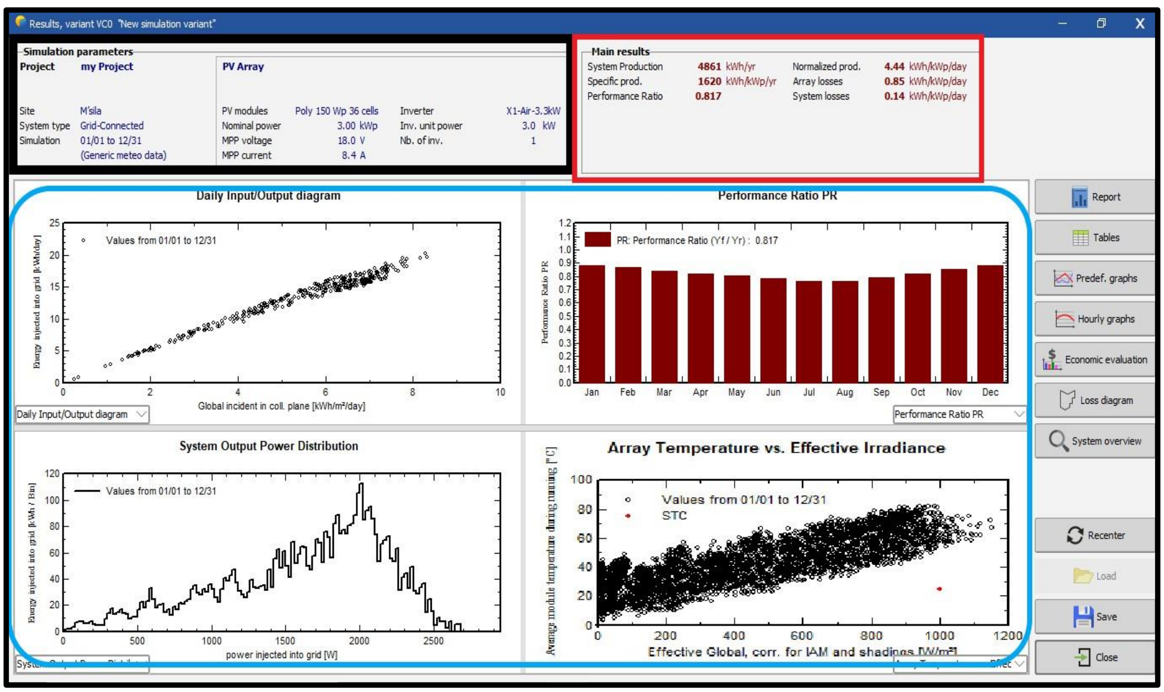

Figure III.11. Results dialog box

III.5.2. The report

Version 7.3.1

PVsyst - Simulation report

Grid-Connected System

Project: Design and installation of a 3 kW
Grid Connected Photovoltaic System

System power: 3000 Wp
M'sila - Algeria

Project: Design and installation of 3 kW grid connected PV system

PVsyst V7.3.1
VC0, Simulation date:
17/02/24 22:13
with v7.3.1

Project summary

Geographical Site	Situation		Project settings	
M'sila	Latitude	35.71 °N	Albedo	0.20
Algeria	Longitude	4.54 °E		
	Altitude	480 m		
	Time zone	UTC+1		

Meteo data
M'sila
Meteonorm 8.1 (1991-2000), Sat=100% - Synthetic

System summary

Grid-Connected System — **No 3D scene defined, no shadings**

PV Field Orientation		Near Shadings	User's needs
Fixed plane		No Shadings	Unlimited load (grid)
Tilt/Azimuth	35 / 0 °		

System information

PV Array		Inverters	
Nb. of modules	20 units	Nb. of units	1 unit
Pnom total	3000 Wp	Pnom total	3000 W
		Pnom ratio	1.000

Results summary

Produced Energy	4861 kWh/year	Specific production	1620 kWh/kWp/year	Perf. Ratio PR	81.70 %

Table of contents

PVsyst V7.3.1
VC0, Simulation date:
17/02/24 22:13
with v7.3.1

Project: Design and installation of 3 kW grid connected PV system

General parameters

Grid-Connected System — **No 3D scene defined, no shadings**

PV Field Orientation			
Orientation	**Sheds configuration**	**Models used**	
Fixed plane	No 3D scene defined	Transposition	Perez
Tilt/Azimuth 35 / 0 °		Diffuse	Perez, Meteonorm
		Circumsolar	separate
Horizon	**Near Shadings**	**User's needs**	
Free Horizon	No Shadings	Unlimited load (grid)	

PV Array Characteristics

PV module		**Inverter**	
Manufacturer	Generic	Manufacturer	Solaxpower
Model	Poly 150 Wp 36 cells	Model	X1-Air-3.3kW
(Original PVsyst database)		(Custom parameters definition)	
Unit Nom. Power	150 Wp	Unit Nom. Power	3.00 kWac
Number of PV modules	20 units	Number of inverters	1 unit
Nominal (STC)	3000 Wp	Total power	3.0 kWac
Modules	1 String x 20 In series	Operating voltage	55-530 V
At operating cond. (50°C)		Pnom ratio (DC:AC)	1.00
Pmpp	2702 Wp		
U mpp	322 V		
I mpp	8.4 A		
Total PV power		**Total inverter power**	
Nominal (STC)	3.00 kWp	Total power	3 kWac
Total	20 modules	Number of inverters	1 unit
Module area	19.8 m²	Pnom ratio	1.00
Cell area	9.4 m²		

Array losses

Thermal Loss factor
Module temperature according to irradiance
Uc (const) 20. W/m²K
Uv (wind) 0. W/m²K/m/s

DC wiring losses
Global array res. 644 mΩ
Loss Fraction 1.5 % at STC

Module Quality Loss
Loss Fraction -0.8 %

Module mismatch losses
Loss Fraction 2. % at MPP

Strings Mismatch loss
Loss Fraction 0.1 %

IAM loss factor
Incidence effect (IAM): Fresnel smooth glass, n = 1.526

0°	30°	50°	60°	70°	75°	80°	85°	90°
1.000	0.998	0.981	0.948	0.862	0.776	0.636	0.403	0.000

PVsyst V7.3.1
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with v7.3.1

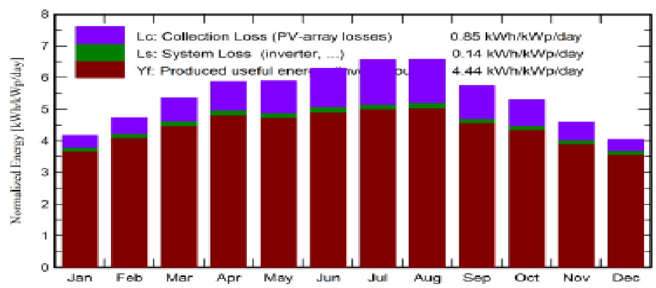
Project: Design and installation of 3 kW grid connected PV system

Main results

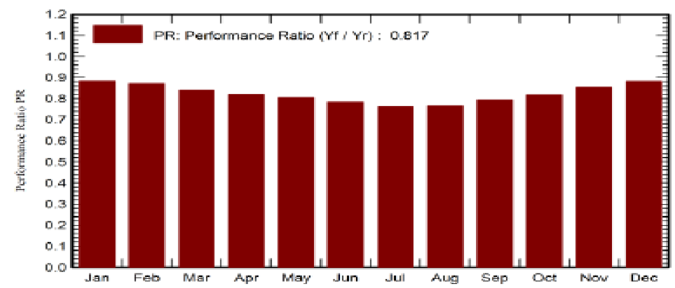
System Production

Produced Energy	4861 kWh/year	Specific production	1620 kWh/kWp/year
		Performance Ratio PR	81.70 %

Normalized productions (per installed kWp)



Performance Ratio PR



Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	80.6	34.17	9.74	129.2	126.8	353.4	342.5	0.883
February	93.0	38.64	11.42	132.3	129.6	356.5	345.5	0.871
March	137.1	55.07	16.30	165.9	162.1	431.0	417.5	0.839
April	168.1	70.28	20.44	176.1	171.2	447.9	433.9	0.821
May	193.5	85.93	25.75	182.8	177.2	455.5	441.3	0.805
June	208.8	90.34	31.13	188.9	182.8	458.0	443.6	0.783
July	219.4	85.61	35.28	203.6	197.4	481.1	466.0	0.763
August	199.9	78.41	34.05	204.0	198.4	484.3	469.2	0.767
September	151.9	61.97	27.82	172.6	168.2	424.7	411.5	0.795
October	122.6	46.10	22.90	164.8	161.3	417.8	404.9	0.819
November	87.2	31.06	14.90	137.5	135.1	364.0	352.8	0.855
December	74.4	29.81	10.64	125.6	123.3	343.2	332.6	0.883
Year	1736.5	707.39	21.76	1983.4	1933.5	5017.4	4861.4	0.817

Legends

GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		

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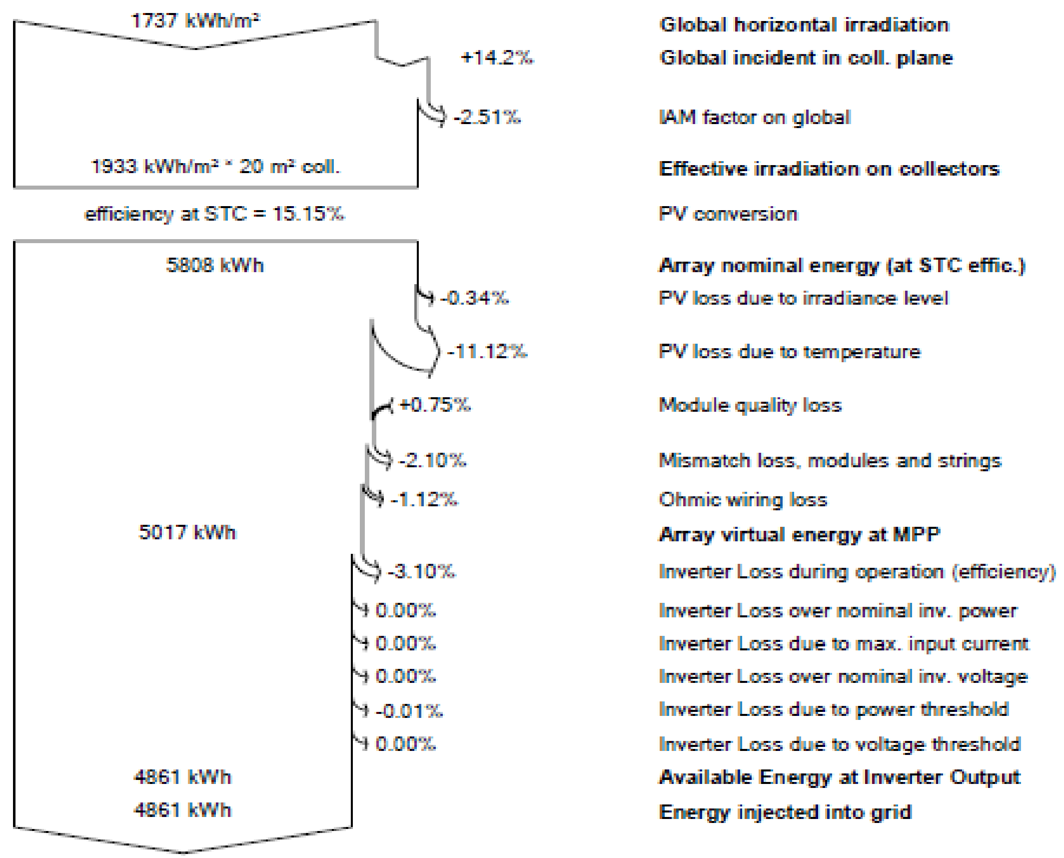
with v7.3.1

Project: Design and installation of 3 kW grid connected PV system

Loss diagram



PVsyst V7.3.1
VC0, Simulation date:
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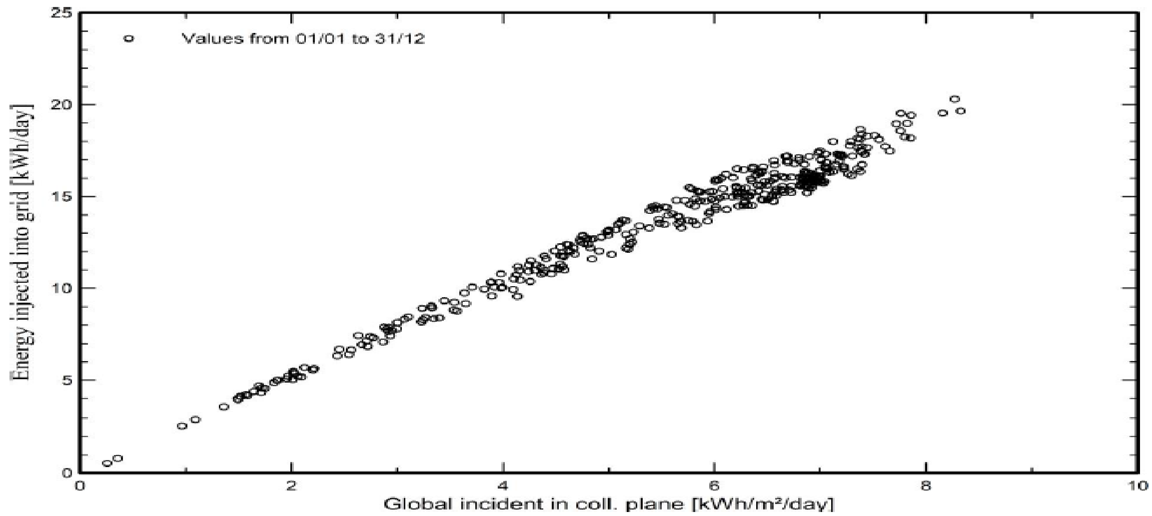
with v7.3.1

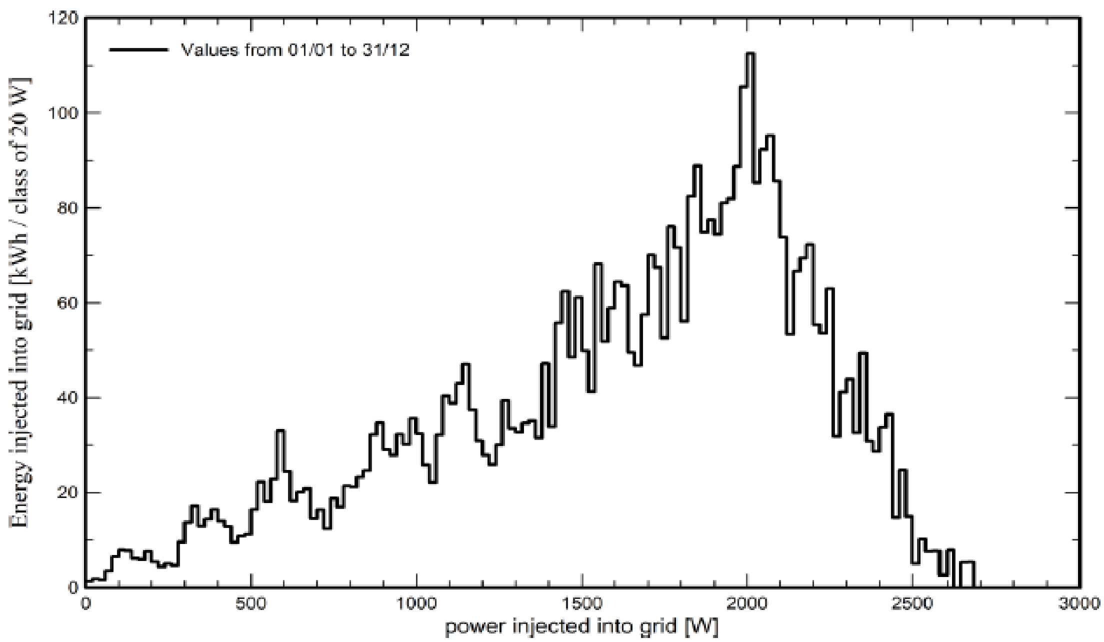
Project: Design and installation of 3 kW grid connected PV system

Predef. graphs

Daily Input/Output diagram



System Output Power Distribution



There are seven pages in this report, which are as follows:

1- Cover page: This contains some information about the project (system type, size, location).
2- Second page: A detailed summary of the project system and results of simulation variables, a fully specified geographic location and weather characteristics, as well as a table of contents of the report.
3- Third page: General basic parameter of the simulation, showing us the level trend, system type, components used configuration table and loss parameters.
4- Fourth page: Contains the main results of the simulation, which are energy production, specific production, and performance ration.
5- Page five: Gives the PVsyst loss chart, which shows the power balance and all losses along the system.
6- Page six: Charts for simulating and showing daily input and output plans and the distribution of forces injected into the network.

III.5.3. Analyze the report results

On the fourth page, I find results related to my system, which are defined in three relevant quantities:

1- Energy produced: The basic result of the simulation, which is equal to 4861kwh/year.
2- Specific production: The produced energy is divided by the facility's nominal energy, which found to be equal to 1620 KWh/kWp/year.
3- Performance ratio: It is an indicator of the quality of the system. This is about 81.7%.

Main results

System Production

Produced Energy	4861 kWh/year	Specific production	1620 kWh/kWp/year
		Performance Ratio PR	81.70 %

Figure III.12. Main simulation results from report

On the same page will also find a table of the main variables, show is monthly values and total annual value. The annual value can be an average, such as temperature, or a sum, such as radiation or energies. The meaning of the different variables is in the image with the table.

Table III.1: assessment and main results of the Msila site

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	80.6	34.17	9.74	129.2	126.8	353.4	342.5	0.883
February	93.0	38.64	11.42	132.3	129.6	356.5	345.5	0.871
March	137.1	55.07	16.30	165.9	162.1	431.0	417.5	0.839
April	168.1	70.28	20.44	176.1	171.2	447.9	433.9	0.821
May	193.5	85.93	25.75	182.8	177.2	455.5	441.3	0.805
June	208.8	90.34	31.13	188.9	182.8	458.0	443.6	0.783
July	219.4	85.61	35.28	203.6	197.4	481.1	466.0	0.763
August	199.9	78.41	34.05	204.0	198.4	484.3	469.2	0.767
September	151.9	61.97	27.82	172.6	168.2	424.7	411.5	0.795
October	122.6	46.10	22.90	164.8	161.3	417.8	404.9	0.819
November	87.2	31.06	14.90	137.5	135.1	364.0	352.8	0.855
December	74.4	29.81	10.64	125.6	123.3	343.2	332.6	0.883
Year	1736.5	707.39	21.76	1983.4	1933.5	5017.4	4861.4	0.817

Legends

GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		

Figure III.13. Table of main variables and its results

Monthly diagrams are presented in units called the normal performance indicator NPI. These variables were defined by the Joint Research Center IRC ISPRA for standardized reporting of PV system performance, and are now defined in the international standard IEC61836.

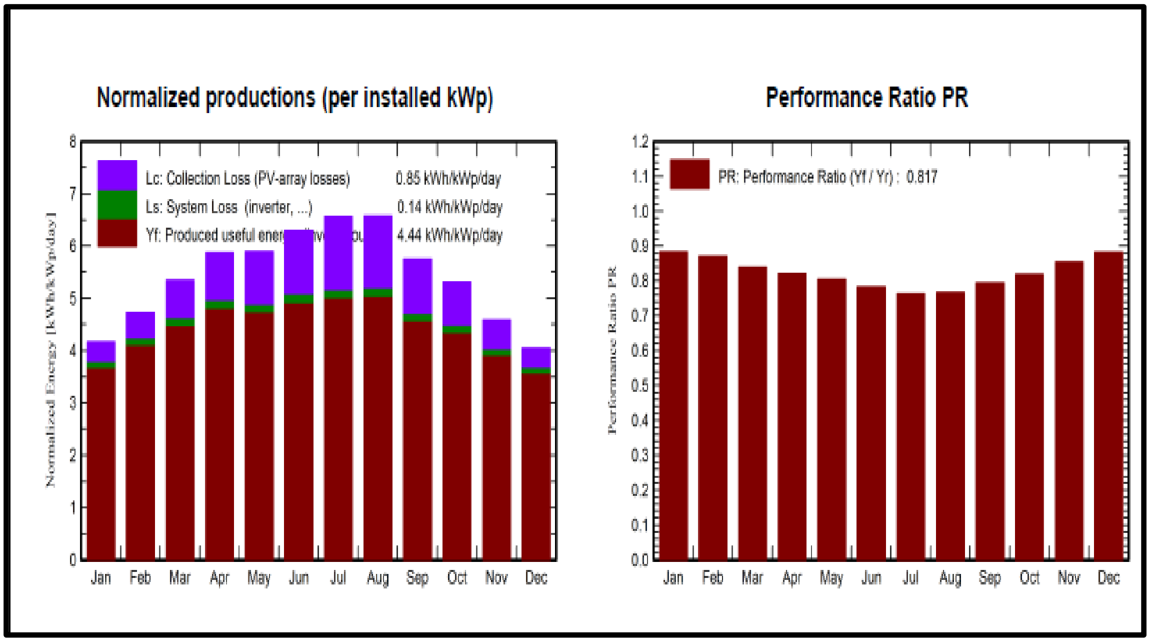


Figure III.14.Standardized performance indices

This figure represents the losses that are influenced on the energy production per month and the corresponding performance index of each state.

These losses are:

- Collection loss: 0.85 kWh/day
- System loss: 0.14kWh/day

When the losses are small the performance index is important and the opposite.

Overall, an APR of 81.7% is considered good for this solar system, indicating that the system is operating at efficiency close to its maximum theoretical potential.

On the fifth page we find the loss diagram that explains all the losses. This chart is very useful for analyzing design options [30], and should be used when comparing systems or variants for the same project

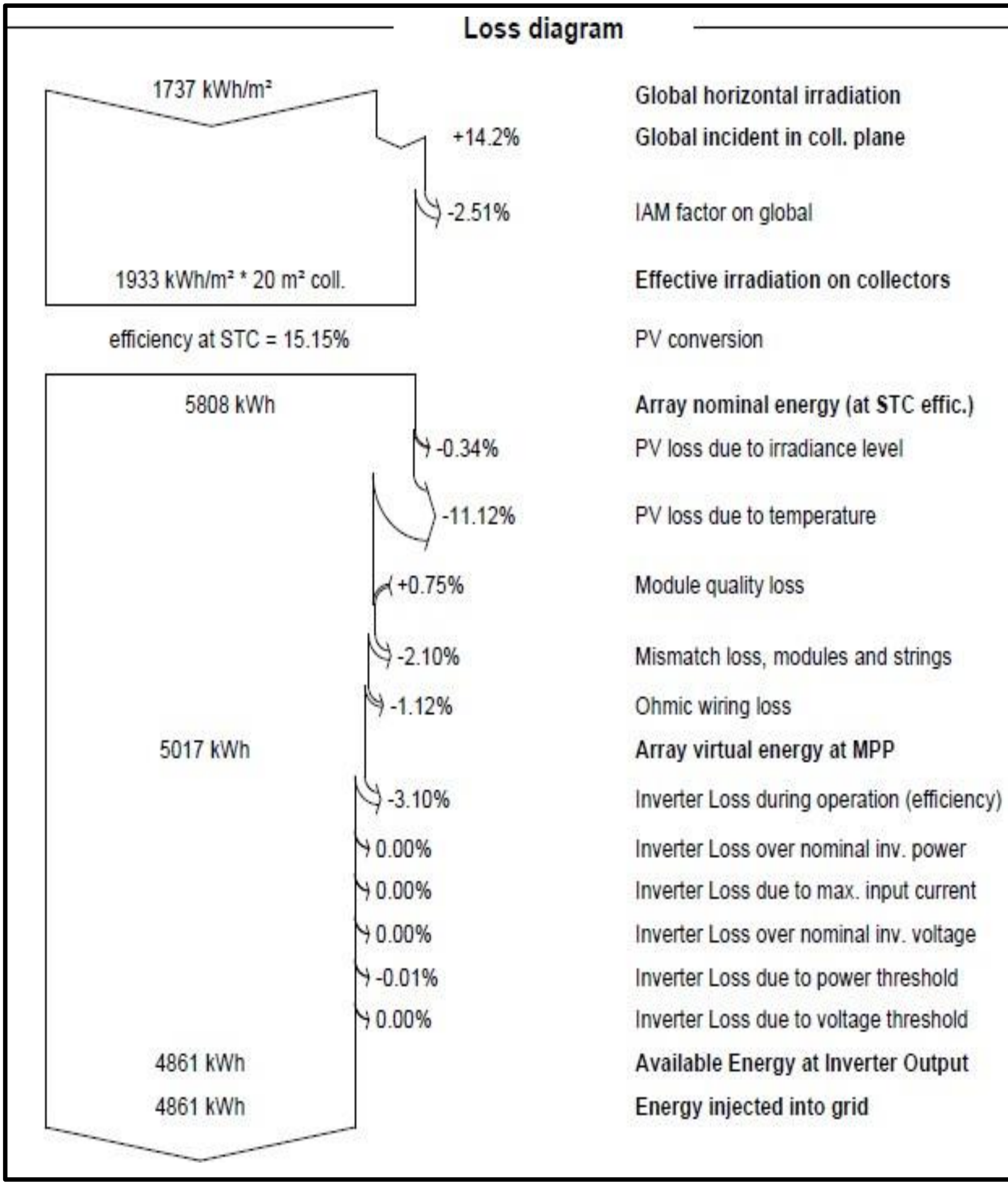


Figure III.15. Loss diagram

III.5.3.1. Loss diagram analysis for PV energy system

1- Global horizontal irradiation: This represents the total solar radiation falling on the surface of the PV modules. It is equal to 1737 kwh/m².

2- Global incident in coll. Plane: This represents the solar radiation that actually reaches the surface of the PV modules, taking into account factors like module orientation and tilt. Increased by 14.2% compared to the global horizontal irradiation.

3- IAM factor on global: The Incidence Angle Modifier (IAM) represents the losses due the angle of incidence of the solar radiation on the PV modules. Decreased by 2.51%.

4- Effective irradiation on collectors: This represents the actual solar radiation that is effectively utilized by the PV modules.no specific value given, but can be calculated from the previous values, as follows :

$$effective\ irradiation\ on\ collectors = \frac{global\ incident\ in\ coll.plane}{global\ horizontal\ irradiation} \quad \text{(III.1)}$$

From the data in the diagram:

- Global horizontal irradiation= 1737 kwh/m²
- Global incident in coll.plane = $1737 \times (1 + 14.2\%) = 1982.4 \frac{kwh}{m^2}$

To calculate the effective irradiation on collectors:

$$effective\ irradiation\ on\ collectors = \frac{1982.4\ kwh/m^2}{1737\ kwh/m^2} \quad \text{(III.2)}$$

= 1.14 or 114%

Therefore, the effective irradiation on collectors is 114%. This indicates that the incident radiation on the surface of the collectors is 14% higher than the global horizontal irradiation, suggesting that the design of the collectors' orientation and tilt is suitable.

5- PV conversion: This represents the conversion efficiency of the PV modules, converting the solar radiation into electrical energy, and efficiency at STC is 15.15%.

6- Array nominal energy (at STC efficiently): This is the expected nominal energy output of the PV array under Standard Test Condition (STC), and equal 5808 kWh.
7- PV loss due to irradiation level: Losses due to the actual irradiation level being different from the STC irradiance. Decreased by 0.34%.
8- PV loss due to temperature: Losses due to the PV module temperature being different from the STC temperature. Decreased by 11.12%.
9- Module quality loss: Losses due to variations in the quality and performance of the PV modules. Increased by 0.75%.
10- Mismatch loss, modules and strings: Losses due to mismatches between the PV modules. Decreased by 2.10%.
11- Ohmic wiring loss: Losses in the electrical wiring and connections. Decreased by 1.12%.
12- Array virtual energy at MPP: The energy output of the PV array Maximum Power Point (MPP), and equal 5017 kWh.
13- Inverter loss during operation (efficiency): Losses in the inverter during the conversion of DC to AC power. Decreased by 3.10%.
14- Inverter loss over nominal inv. power: Losses in the inverter when operating at non-nominal power levels. Around 0.00% or close to it.
15- Inverter loss due to max. Input current: Losses in the inverter due to exceeding the maximum input current. Around 0.00% or close to it.
16- Inverter loss over nominal inv. voltage: losses in the inverter due to exceeding the nominal input voltage. Around 0.00% or close to it.
17- Inverter loss due to power threshold: Losses in the inverter when the power output is below the minimum threshold. Around 0.00% or close to it.
18- Inverter loss due to voltage threshold: Losses in the inverter when the voltage output is below the minimum threshold. Around 0.00% or close to it.
19- Available energy at inverter output: The final energy output of the PV system, which is the energy injected into the grid, and equal 4861kWh.

Analyzing these values, we can extract some points:

1- The global incident radiation on the surface increased by14.2% compared to the global horizontal irradiation, indicating that the tilt and orientation of the solar collectors are suitable.
2- There are significant losses due to temperature (11.12%), suggesting the need for better cooling of the modules or the use of more heat-resistant modules.
3- The mismatch and ohmic wiring losses to 3.22%, indicating the need to improve electrical connections and balance the array.
4- The inverter losses during operation were 3.10%, which is a reasonable value for the inverter efficiency.
5- The final available energy at the inverter output is 4861 kWh, which is 83.7% of the array nominal energy at STC.

This detailed analysis of the values in this loss diagram provides a comprehensive view of the system's performance and potential areas for improvement.

III.6. Conclusion

Throughout this chapter, we highlighted the main steps in the development and modeling of the proposed photovoltaic system. We started by introducing the PV system design tool and the PVsyst software, and then proceeded to build a model of the targeted system and implement the simulation process and its in-depth analysis. These systematic stages helped us acquire a comprehensive understanding of the design and performance of this proposed photovoltaic system.

These findings and conclusions will be of great importance in supporting the next step in this study, which is the conduction of an in-depth economic assessment of the project in the upcoming chapter. This economic analysis will help provide deep insights into the financial feasibility of implementing this photovoltaic project and will be a crucial element in the final decision-making regarding its potential execution.

Chapter IV:

Economic Assessment

IV.1. Introduction

Conducting an economic feasibility analysis for solar energy projects is a crucial step to ensure their success and financial viability. In this chapter, a comprehensive economic study will be carried out for a 3 kWh grid-connected solar power project, focusing on the key financial factors and indicators.

Initially, the assumptions and data used in the economic analysis will be identified, such as the discount rate, purchase price, evolution of the kWh price, and degradation rate. Subsequently, the initial costs of the project will be calculated, including equipment.

Then, a detailed financial analysis will be performed, encompassing the calculation of energy production and expected revenue, as well as annual net cash flow. Major financial evaluation metrics, such as net present value (NPV), internal rate of return (IRR), levelized cost of energy (LCOE), and discounted payback period (DPP), will be utilized to assess the project's profitability and feasibility.

Finally, the financial results will be discussed, and the impact of various factors on the project's profitability will be examined. This comprehensive economic analysis will aid in making an informed decision regarding the implementation of this solar power project.

IV.2. Project Description

IV.2.1. Initial costs of the project

Initial costs of a project refer to the one-time expenses incurred at the beginning or during stages of a project's life cycle. These costs are typically associated with the initial investment required to get the project up and running [31].

The initial costs of a project can vary significantly depending on the project's nature, size, and complexity.

Accurately estimating and budgeting for the initial costs a crucial during the project planning phase, as it helps determine the project's feasibility, secure necessary funding, and evaluate its potential return on investment. Initial costs are also an essential factor in calculating the project's net present value NPV and other financial metrics used for decision-making and investment analysis [31].

The tables IV.1 represent all project materials costs.

Table IV.1. The initial costs of the project

	The materials	Unit	Quantity	Unit Price	Total Price
Panels	Polycrystalline solar panel, Puissance:125W/Tension:24V	Wc	20	21750 DA	435000 DA
Inverter	Single-phase on-grid 3KW	W	1	223000 DA	223000DA
Structure	Triangular metal structure for 20 panels	_	1	133000 DA	133000 DA
Cables	Bare Copper 6 mm2	m	100	450 DA	45000 DA
The Boxes					
Boxe DC	Fuse holder 16A	_	2	1500 DA	3000 DA
	Isolater switch 16A	_	1	6500 DA	6500 DA
	Surge protecter 20KA	_	1	5000 DA	5000 DA
Boxe Ac	Differential circuit breaker 25A	_	1	4000 DA	4000 DA
TOTAL HT					854500 DA
TVA 19%					162355 DA
TOTAL TTC					1016855 DA

IV.2.2. Assumption and data used in the economic analysis

This information is available on the website of the Ministry of Energy and Mines in Algeria.

a. Discount rate: the discount rate used for solar projects is usually 8%.

b. Evolution of the price of kWh: according to the Ministry's policies, the annual change in kWh prices is expected to be within 5% in the coming years.

c. Degradation rate: the annual degradation rate of solar energy systems in Algeria is estimated at about 2% per year.

IV.2.2.1. Discounted rate

The discounted rate is the rate at which future cash flows are converted to their present value [32]. It is used to calculate the net present value NPV of a project, where future cash flows are discounted using this rate to determine their present value [33].

IV.2.2.2. Degradation rate

The degradation rate is the rate at which the performance efficiency of a solar system or solar panels [34] decreases over time. This degradation occurs due to various factors such as environmental impacts and natural aging of materials [34]. The degradation rate is used in financial analysis calculations to estimate the amount of energy that solar panels will produce over their expected lifetime [34].

IV.2.2.3. Selling price

The selling price is the monetary amount received in exchange for selling a product or providing a service.

IV.2.2.4. Evolution of the price of kWh

Evolution of price in solar power projects refers to the changes in the price at which the electricity generated from a solar power system is sold to the grid over the project's lifetime. This price may vary from year to year due to various factors such as changes in operation and maintenance costs, financing costs, and any regulatory or governmental changes in renewable energy support policies [31].

The table IV.2 represents project data

Table IV.2. The data of the project

Investment	1016855 DA
Discount rate (%)	8%
Kwh purchase price (DA/Kwh)	7 DA
Evolution of the price of Kwh (%/year)	5%
1st year solar production (Kwh)	21024
Degradation rate per year (%)	2%

IV.2.2.5. Project lifespan

This photovoltaic project is designed to operate efficiently for a full 25 years, during which is main components, such as solar panels, inverter, and others, are expected to remain in good condition throughout this estimated period, with the necessity of carrying out periodic maintenance operations to maintain their optimal performance levels.

IV.3. Financial analysis

IV.3.1. Energy production and revenue calculations

IV.3.1.1. Calculation of annual energy production

We have:

- System capacity 3kWh
- System power factor 0.8, that is produces 80% of its energy [of inverter datasheet]
- Number of hours per year 8760 hours

So, the energy produced in the first year is:

$$E = C \times PF \times N_h \tag{IV.1}$$

$$E = 21024\ kWh$$

Then, calculation of the energy produced in the different year:

$$E_{(n+1)} = E_{(n)} - [E_{(n)} \times r] \tag{IV.2}$$

$$E_{(n+1)} = E_{(n)} \times (1 - r)$$

Where:

$_{(n+1)}$: The energy production for the next year

$_{(n)}$: The energy production for the current year

r: Degradation rate (%)

r=2%=0.02

$$E_{(n+1)} = E_{(n)} \times 0.98$$

We have: $E_1 = 21024$ kWh so:

$E_2 = E_1 \times 0.98 = 21024 \times 0.98 = 20603.52 kWh$

$E_3 = E_2 \times 0.98 = 20603.52 \times 0.98 = 20191.4496 kWh$

$E_4 = E_3 \times 0.98 = 20191.4496 \times 0.98 = 19787.62061 kWh$

In this way, the energy produced is calculated over the life of the project.

IV.3.1.2. Calculation of annual energy price

The starting price is 7DA and the evolution of the price of the kWh is 5%

$$P_{(n+1)} = P_{(n)} \times (1 + 0.05) \quad \text{(IV.3)}$$

Where:

$P_{(n+1)}$: The energy price for the next year

$P_{(n)}$: The energy price for the current year

$P_1 = P_0 \times (1 + 0.05) = 7 \times (1 + 0.05) = 7.35 DA$

$P_2 = P_1 \times (1 + 0.05) = 7.35 \times (1 + 0.05) = 7.7175 DA$

$P_3 = P_2 \times (1 + 0.05) = 7.7175 \times (1 + 0.05) = 8.103375 DA$

In this way, the energy price is calculated over the life of the project.

IV.3.1.3. Calculation of annual revenue

Revenue refers to the income generated by the solar energy project through the sale of the electricity it produce.

In the case of this project, the main and only revenues will be from the sale of the electricity produced, and these revenues will constitute the cash flow coming into the project. Revenue is calculated by this way:

$$R = \text{solar production} \times \text{price} \quad \text{(IV.4)}$$

$R_1 = E_1 \times P_1 = 21024 \times 7.35 = 154526.4 DA$

$R_2 = E_2 \times P_2 = 20603.52 \times 7.7175 = 159007.6656 DA$

$R_3 = E_2 \times P_2 = 20191.4496 \times 8.103375 = 163618.8879 DA$

In this way, revenue is calculated

IV.3.2. Cash flow calculations

IV.3.2.1. Calculation of cash flow

Cash flow refers to the inflows and outflows of cash and cash equivalents of an entity (company, project, etc.) over a specific period of time. Cash flow is considered an important indicator of the financial health of the entity and its ability to meet its financial obligations [35].

In the case of this project, the cash flow can be calculated as follows:

$$\text{cash flow} = \text{revenue} - \text{costs} \tag{IV.5}$$

Where revenues are the amounts received from the sale of produced electricity, and costs include the initial investment, and any annual operational or maintenance costs.

In this project, there are no costs, only the initial costs.

In year 0:

$$\text{Cash flow} = 1016855 - 1016855 = 0\text{DA}$$

In subsequent years, cash flow = revenue (no additional costs).

Year 1: cash flow = revenue =154526.4 DA

Year 2: cash flow = revenue =159007.6656 DA

Year 3: cash flow = revenue =163618.8879 DA

And all the remaining years are like this.

IV.3.2.2. Calculation of annual net cash flow

Annual net cash flow is the net amount of cash inflows and outflows from an entity (company, project, etc.) over the course of a single year [35] or the annual net cash flow is the difference between the cash inflows.

The annual net cash flow can be calculated as flows:

$$C_{AV} = \text{cash flow}(\text{year}_{(n+1)}) - \text{cash flow}(\text{year}_{(n)}) \tag{IV.6}$$

Year 1:

$$C_{AV} = cash\ (ye_{(1)}) - cach\ (year_{(0)})$$

$C_{AV1} = 154526.4 - (-1016855) = 1171381.4\text{DA}$

Year 2:

$\text{C}_{\text{AV}} = \text{cash flow (year}_{(2)} - \text{cash flow (year}_{(1)})$

$\text{C}_{\text{AV2}} = 159007.6656 - 154526.4 = 4481.2656\text{DA}$

And all the remaining years are like this.

IV.3.3. Net present value (NPV)

IV.3.3.1. Concept of NPV

Net present value NPV is a financial analysis tool used to estimate the viability of a project or investment. It is used to find the total present value of all future cash flows [36]. The net present value is calculated by subtracting the initial investment amount from the total present value transferred [36].

IV.3.3.2. Calculation of the project's NPV

$$\text{NPV} = \sum_{t=1}^{N} \frac{\text{C}_{\text{AV}}}{(1+\text{d})^{\text{N}}} - \text{C}_0 \qquad \text{(IV.7)}$$

Where:

C_0: Initial investment (DA)

C_{AV}: Annual net cash flows (DA)

d: Discount rate (%)

$N\text{PV} = 123636.2598\text{DA}$

$\text{NPV} > 0$

IV.3.4. Internal rate of return IRR

IV.3.4.1. Concept of IRR

The internal rate of return is the rate that makes the NPV of a series of cash flows equal to zero. Simply put, it is the rate that equates the present value of cash inflows with the present value of cash outflows [37]. The IRR is used as a measure of the profitability and financial viability of a particular investment project.

IV.3.4.2. Calculation of the project's IRR

To calculate the internal rate of return, a mathematical formula is used based on the trial and error method using the NPV equation.

The steps to calculate the IRR are:

- Assume a value for the discount rate.
- Calculate the NPV using this assumed rate and the project's cash flow series.
- If he NPV is equal to or close to zero, the assumed discount rate is the internal rate of return IRR.
- If the NPV is negative, it means that the assumed discount rate is greater than the IRR, and should lower the discount rate.
- We repeat the steps using different discount rates until we reach an NPV value of zero or almost zero, which will be the internal rate of return IRR.

Now we will impose this value of NPV: 10/11/12/16/17.50/17.60/18/18.20/19/20.50 and we will perform the detailed calculation using Excel and the results are shown in the following tables:

R	8%	r	10%	r	11%
Total	1140491	Total	1110701.786	Total	1097052.82
NPV	123636	NPV	93846.78578	NPV	80197.8166
R	12%	r	16%	r	22.50%
Total	1084091.93	Total	1037639.26	Total	974629.207
NPV	67236.9321	NPV	20784.2552	NPV	-4225.7928
R	19%	r	17.50%	r	17.60%
Total	1007029.71	Total	1021761	Total	1020943.42
NPV	-9825.29233	NPV	4905.842	NPV	4088.4
R	18%	r	18.20%		
Total	1016905.85	Total	1014906.17		
NPV	50.85	NPV	-1948.82596		

Figure IV.1. Different results of net present value

After calculation, we find that the NPV is close to zero and positive when the discount rate is 18%, so the IRR of project is 18%.

IV.3.5. Levelized cost of energy LCOE

IV.3.5.1.Concept of LCOE

Levelized cost of energy represents the average cost of producing one unit of electrical energy over the life of the project [38]. The lowest possible levelized must be achieved.

IV.3.5.2.Calculation of the project's LCOE

To calculate the levelized cost of energy, we use the following mathematical formula:

$$\text{LCOE} = \sum \frac{C_0 + C_{O\&M} + C_E}{\text{Energy Generated}} \qquad \text{(IV.8)}$$

Where:

C_0: Initial investment (DA)

$C_{O\&M}$: Operational and maintenance costs (in this project equal zero

C_E: Fuel cost (in PV system $C_E = 0$)

$\text{LCOE} = 2.35\ \text{DA/kWh}$

IV.3.6. Discounted payback period DPP

IV.3.6.1.Concept of DPP

The period of time required to recover the capital cost through inflows while discounting future cash flows.

Calculation of the project's DPP

$$\text{DPP} = \sum \frac{\text{Cash Flow}}{(1+r)^t} \qquad \text{(IV.9)}$$

- Calculate the discount factor for each year:

$$\text{DF} = \frac{1}{(1+r)^t} \qquad \text{(IV.10)}$$

Year 1: $DF = \frac{1}{(1+0.08)^1} = 0.926$

Table IV .3: The discount factor of each year

Year	Discount factor
1	0.926
2	0.857
3	0.794
4	0.735
5	0.680
6	0.630
7	0.583
8	0.540
9	0.5
10	0.463

We complete the calculation over the life of the project.

Calculate the discount cash flow for each year:

$$DCF = CF \times DF \qquad \text{(IV.11)}$$

Year 1: $DCF_1 = CF_1 \times DF_1 = 14526.4 \times 0.926 = 143091.446$

Table IV.4: The discount cash flow for each year

Year	Discount cash flow
1	143091.446
2	136269.569
3	129913.397
4	123747.419
5	117807.543
6	112310.435
7	107035.626
8	101935.34
9	97117.096
10	92537.958

Sum DCF until it exceeds the investment cost.

Table IV.5: Total discount cash flow

Year	DCF	Note
1+2	279361.01	Less than initial cost
1+2+3	409274.41	Less than initial cost
1+2+3+4	533021.83	Less than initial cost
1+2+3+4+5	650829.37	Less than initial cost
1+2+3+4+5+6	763139.81	Less than initial cost
1+2+3+4+5+6+7	870175.44	Less than initial cost
1+2+3+4+5+6+7+8	972110.78	Less than initial cost
1+2+3+4+5+6+7+8+9	1069227.88	Greater than initial cost
1+2+3+4+5+6+7+8+9+10	1162765.83	Greater than initial cost

Therefore, the discounted payback period for this project is 9 years. After 9 years, the discounted cash flows would have exceeded the initial cost of the project.

IV.4. Results Discussion

IV.4.1. Analysis of financial results

- Net present value NPV= 123636.26 DA
  - The positive NPV value indicates that the project is economically viable and generates a return higher than the 8% discount rate used.
- Internal rate of return IRR=18%
  - The IRR of 18% is significantly higher than the 8% discount rate, meaning the project achieves a good return on investment.
  - An 18% IRR can be considered acceptable and profitable for this project.
- Levelized cost of energy LCOE=2.35DA
  - Compared to the assumed selling price of 7 DA, the LCOE indicates that the project will be profitable.
  - The low LCOE compared to conventional electricity prices in Algeria makes solar energy an attractive option.
- Discount payback period DPP= 9 years
  - A 9 years payback period is reasonable for this project.
  - A 25 years lifetime for the system, there will be enough time to generate profits after recovering the capital investment.

Overall, the financial results obtained are positive and indicate that this 3 kW grid connected PV system project will be economically viable and profitable in the long run. The high IRR, positive NPV, and reasonable payback period support the project's feasibility.

IV.5. Conclusion

In conclusion, a comprehensive economic analysis was conducted for the 3kW grid connected PV system project. By examining various financial aspects of the project, important conclusions were drawn regarding its economic feasibility.

The calculations of net present value NPV and internal rate of return IRR demonstrated that the project will be profitable in the long run, with positive cash flows outweighing the initial and operational costs. Furthermore, the low livelized cost of energy LCOE indicates that the electricity produced will be within competitive market prices.

Overall, this solar power project can be considered an attractive investment opportunity, especially with the increasing trend towards renewable and clean energy sources.

General Conclusion

General Conclusion

The work presented in this thesis concerns the design and analysis a 3kW grid connected photovoltaic system for powering LGE laboratory at the faculty of technology. This project represents an important step towards transitioning to renewable energy sources and reducing reliance on fossil fuels, thereby contributing to the preservation of the environment and natural resources.

The project has been comprehensively studies in this thesis, covering all aspects related to the design, installation, and operation of the photovoltaic system. Additionally, a simulation of the system was conducted using the specialized PVsyst software, enabling an accurate evaluation of its performance and analysis of the results.

Furthermore, the in-depth economic study provided valuable insights into the financial feasibility of the project, where initial costs, future cash flows, and economic feasibility indicators such as net present value, internal rate of return, levelized cost of electricity, and discount payback period were calculated. The results demonstrated that the project has good long-term economic viability.

Despite the challenges encountered during the implementation of this project, they were overcome through continuous efforts and ongoing learning. One of the key lessons learned is the importance of careful planning and effective coordination among all stakeholders to ensure the success of renewable energy projects.

In light of the positive results of this project, the mandate is to encourage the wider adoption of photovoltaic solar energy in Algeria, both at residential, industrial, and institutional levels. There isalso call for further investment in research and development to improve the efficiency and effectiveness of solar energy technologies and reduce their costs.

Ultimately, renewable energy, particularly photovoltaic solar energy, represents the future of sustainable and environmentally friendly energy. The transition towards these technologies will undoubtedly contribute to ensuring energy provision for future generations without compromising the environment or depleting natural resources. Projects like this thesis represent a step in the right direction towards a more sustainable future.

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