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**Thème :**

**Techno-Economic Evaluation and Optimization of Smart Solar-Powered Residential Systems**

|                             |            |                                          |                   |
|-----------------------------|------------|------------------------------------------|-------------------|
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## Dedication

إهداء عائلتي إلى القلبين اللذين علماني أن الأحلام تصنع بالصبر، وأن النجاح لا يأتي إلا بعد تعبٍ ودعاء...

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”

"رزقة الاء الرحمان"





## Dedication

“من قال أنا لها نالها”

وأنا لها وإن أبت رغما عنها أتيت بها، لم تكن الرحلة قصيرة ولا ينبغي لها أن تكون،

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## *Abbreviations and symbols*

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### **Abbreviations and symbols**

**$I_c$ :** the output current generated by the photovoltaic cell.

**$I_{ph,c}$ :** the photocurrent produced by the incident solar radiation on the cell.

**$I_{0,c}$ :** the reverse saturation current of the diode inside the photovoltaic cell.

**$V_c$ :** the voltage across the photovoltaic cell terminals.

**$R_{s,c}$ :** the series resistance of the cell, related to internal electrical losses.

**$R_{sh,c}$ :** the shunt (parallel) resistance, associated with leakage currents inside the cell.

**$q$ :** the elementary electron charge.

**SOC:** State of Charge of the battery.

**$V_{bat}$ :** Battery voltage.

**$I_{bat}$ :** Battery current.

**$P_{bat}$ :** Battery power.

**$R_{self}$ :** Self-discharge resistance of the battery.

**$P_{pv}$ :** Power generated by the photovoltaic panels.

**$V_{pv}$ :** Output voltage of the photovoltaic panels.

**$I_{pv}$ :** Output current of the photovoltaic panels.

**$P_{load}$ :** Electrical load power.

**$V_{ac}$ :** Alternating current (AC) output voltage from the inverter.

**$I_{ac}$ :** Alternating current (AC).

**Freq:** Electrical frequency.

**DC:** Direct Current.

**AC:** Alternating Current.

**EMS:** Energy Management System.

---

**IoT:** Internet of Things.

**PWM:** Pulse Width Modulation used for electronic control.

**MPPT:** Maximum Power Point Tracking used to optimize solar panel performance.

**BESS:** Battery Energy Storage System.

**RES:** Renewable Energy Sources.

**ESS:** Energy Storage System.

**PEVs:** Plug-in Electric Vehicles.

**NPC:** Net Present Cost.

**LCOE:** Levelized Cost Of Energy.

**ROI:** Return On Investment.

**IRR:** Internal Rate of Return.

**PV:** Photovoltaic System.

**BESS:** Battery Energy Storage System.

**EMS:** Energy Management System.

**ESS:** Energy Storage System.

**RES:** Renewable Energy Sources.

**IoT:** Internet of Things.

**MPPT:** Maximum Power Point Tracking.

**PWM:** Pulse Width Modulation. **PEVs:** Plug-in

Electric Vehicles.

**DC:** Direct Current.

**AC:** Alternating Current.

**Li-ion:** Lithium-Ion Battery.

### *Abbreviations and symbols*

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**GEL:** Gel Battery Technology.

**NPC:** Net Present Cost.

**LCOE:** Levelized Cost Of Energy.

**ROI:** Return On Investment.

**IRR:** Internal Rate of Return.

**SOC:** State Of Charge.

**BMS:** Battery Management System.

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# ***General Introduction***



## **General Introduction**

The growing demand for electrical energy, combined with the depletion of fossil fuel resources and increasing environmental concerns, has become one of the major challenges facing modern societies. Conventional energy production methods are associated with greenhouse gas emissions and environmental degradation, which has encouraged the search for cleaner and more sustainable alternatives.

Among the various renewable energy sources, solar photovoltaic (PV) technology has emerged as one of the most promising solutions due to its abundance, environmental friendliness, and continuous technological development. However, the intermittent nature of solar energy and the variability of electrical demand may affect the reliability and efficiency of photovoltaic systems. To overcome these limitations, several solutions have been proposed, including energy storage systems, grid integration, advanced power electronic converters, and intelligent energy management strategies.

In this context, the present work focuses on the study and analysis of a photovoltaic system integrated with an Energy Management System (EMS). The adopted approach aims to improve the operation of the system, optimize energy utilization, and ensure a better balance between energy production and consumption. Modeling and simulation tools are employed to evaluate the performance of the proposed system under different operating conditions.

This dissertation is organized into three chapters.

Chapter I presents the theoretical background and literature review related to renewable energy, photovoltaic systems, and intelligent energy management concepts.

Chapter II describes the structure, components, and mathematical modeling of the proposed photovoltaic system and its energy management strategy.

Chapter III is devoted to the simulation of the system and the analysis of the obtained results in order to evaluate its technical and economic performance.



# ***Chapter I:***

## ***Literature Review and Conceptual Framework***

## **I. 1.Introduction**

The energy sector globally, and particularly in Algeria, is undergoing rapid transformations due to increasing demand for electricity and the shift towards renewable energies, especially solar power. With technological advancements, integrating smart technologies such as the Internet of Things (IoT) and energy management systems into home solar systems has become essential to improve efficiency and optimize consumption. This chapter aims to present the current state of the energy sector and introduce the key concepts and technologies being adopted.

## **I.2.The Energy Context in Algeria and the Transition to Solar Energy**

### **I.2.1. Energy Context in Algeria:**

The Algerian energy context is characterized by a strong dependence on hydrocarbons, particularly natural gas and oil, both for electricity production and for the entire national economy. Algeria is among the world's leading energy producers and exporters, and the energy sector plays a strategic role in economic development and national energy supply.

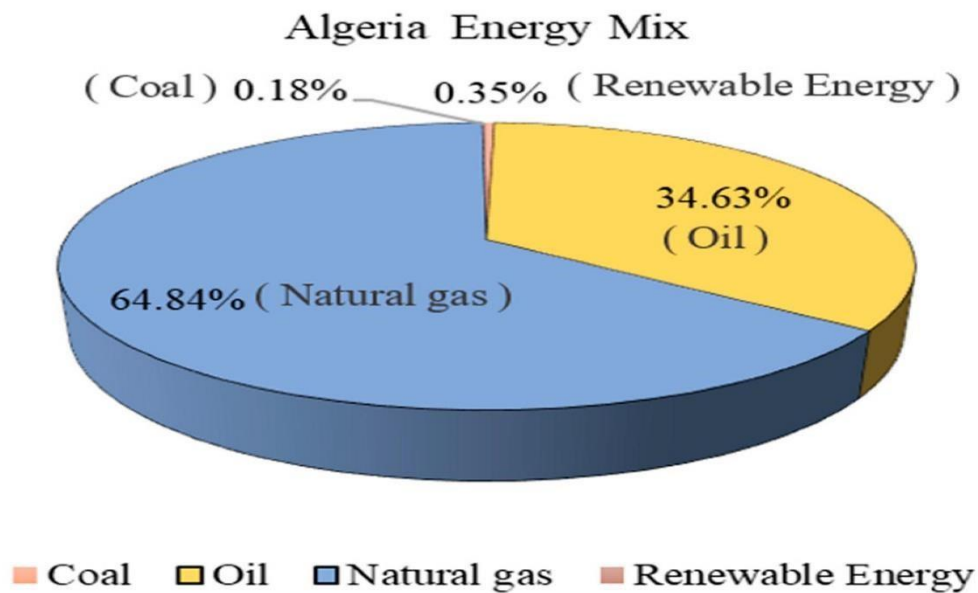
#### **a) Strong Dependence on Hydrocarbons:**

The Algerian energy system relies heavily on natural gas and oil as its main energy sources. Algeria possesses significant natural gas reserves and is among the world's largest exporters, particularly to Europe.

Natural gas is widely used for electricity production, with several reports indicating that over 90% of Algeria's electricity production relies on this gas. As a result, the country's energy mix is almost entirely dependent on fossil fuels.

The hydrocarbon sector also plays a significant role in the national economy, contributing substantially to:

- Export revenues.
- Government revenues.
- Financing of development projects .[1]



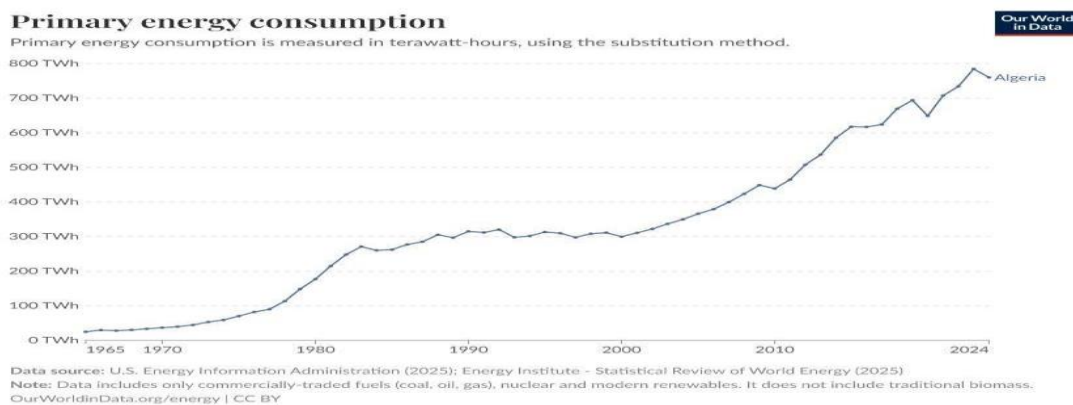
**Figure I. 1:** Distribution of the energy mix in Algeria [1]

**b) Increased Energy Demand:**

Algeria has experienced a sharp increase in its energy and electricity demand in recent years, due to several factors, including:

- Population growth.
- Urban expansion .[2]
- Development of the industrial sector.
- Increased use of refrigeration and air conditioning.

This sharp rise in demand is putting increasing pressure on electricity production, prompting the government to seek new solutions to diversify its energy sources. [3]



**Figure I. 2:** Evolution of electricity demand in Algeria [2-4]

### **I.2.2.The Shift Towards Renewable Energies:**

Faced with the challenges of its heavy reliance on hydrocarbons, Algeria has begun a gradual transition to renewable energies, particularly solar energy, for the following reasons:

- Algeria benefits from abundant sunshine, especially in its desert regions.
- The desire to reduce gas consumption for electricity generation.
- Diversification of the energy mix.
- Reduction of carbon emissions.

The Algerian government has launched several renewable energy development programs, such as the National Renewable Energy Development Program (PNDR), which aims to produce thousands of megawatts of solar energy in the coming years. [4]

### **I.2.3.Challenges in the Energy Sector:**

Despite its considerable potential, the Algerian energy sector faces several challenges, including:

- A strong dependence on fossil fuels. • High domestic energy consumption.
- The need for substantial investments in renewable energy.
- The volatility of oil and gas prices on global markets .[5]

#### **a) The Importance of the Energy Transition:**

For these reasons, the energy transition in Algeria has become a strategic necessity to guarantee the sustainability of energy resources and ensure economic development. This transition aims to :

- Diversify energy sources . [6]
- Dynamiser la production d'énergies renouvelables
- Améliorer l'efficacité énergétique
- Réduire la dépendance aux hydrocarbures .[7]

### **I.2.4.Transition to Solar Energy:**

Algeria possesses considerable potential for solar energy production thanks to its geographical location, which ensures abundant sunshine throughout the year, particularly in desert regions. Consequently, solar energy has become a strategic option for the energy transition and reducing dependence on fossil fuels .[8]

**a) Reasons for the Transition to Solar Energy:**

Heavy Dependence on Natural Gas and Oil: Most fuels are used for electricity generation, making the energy mix vulnerable to fluctuations in global markets.

Strong Solar Potential: Algeria benefits from approximately 2800 to 3000 hours of sunshine per year, making it one of the most suitable countries for solar energy production.

Carbon Emission Reduction: Solar energy is a clean energy source that reduces greenhouse gas emissions compared to fossil fuels.

Energy Diversification: The transition to solar energy helps reduce dependence on oil and gas and ensures a sustainable electricity supply for cities and the industrial sector. [9]

**b) Solar Energy Projects in Algeria:**

Algeria has a national renewable energy program aiming to produce thousands of megawatts of solar power by 2035.

Large-scale projects in desert areas, such as the Hassi Messaoud solar power plant and other projects in the Algerian Sahara, take advantage of the vast expanses and abundant sunshine.

Integrating solar energy into the electricity grid helps reduce pressure on gas-fired power plants and improve the stability of the national grid .[9]



**Figure I.3:** Example of a solar power plant in Algeria: The Ghardaïa photovoltaic power plant

### c) Challenges:

High initial investment costs: Establishing large-scale solar power plants requires substantial investment. Lack of infrastructure and advanced technologies: The sector needs to develop smart grids and connect solar power plants to the main grid. Energy storage: Because solar energy is intermittent, Algeria needs efficient storage solutions to ensure a continuous supply.

[9]

### d) Expected Benefits:

Reduce dependence on natural gas for electricity generation. Decrease harmful emissions and protect the environment. Create new investment and industrial opportunities in the renewable energy sector. Strengthen energy independence and ensure the stability of the electricity grid. [9]

### **I.3.Residential Solar Systems: General Information**

#### **I.3.1. Definition of Residential Solar Systems:**

Residential solar systems encompass the technologies and methods used in homes to produce electricity or heat water using solar energy. These systems primarily rely on solar panels that convert sunlight into electrical or thermal energy, which can then power various household appliances or provide domestic hot water. They are among the most important renewable energy solutions in the residential sector, as they significantly contribute to reducing conventional electricity consumption and, consequently, long-term energy costs. [10]

#### **I.3.2. Components of a Residential Solar System:**

A typical home solar system consists of several essential components:

- Solar panels: These convert sunlight into direct current (DC).
- Inverter: This converts the DC into alternating current (AC), compatible with household appliances.
- Batteries: These store energy for nighttime use or during power outages.
- Charge controller: This regulates the charging of the batteries and protects them from overcharging.
- Mounting kits and heavy-duty cables: These allow you to attach the panels to the roof and connect the various system components. [11]

#### **I.3.3. Direct connection to the public electricity grid:**

- No batteries are required.
- Reduced electricity bills.

#### **Types of Residential Solar Systems:**

Residential solar systems are divided into three main categories:

- Grid-tied system:
- Off-grid system:

- o independent operation, without grid connection.
- o Uses batteries for energy storage.
- o Often used in remote or rural areas.
- Hybrid system:
  - o Combination of grid connection and battery storage.
  - o Offers greater flexibility and a more stable power supply. [12]

## **I.4.Smart Technologies: IoT, Smart Meters, EMS**

Technological advancements in the energy sector have led to the emergence of smart technologies designed to improve energy efficiency and accurately monitor consumption. Among the most important are the Internet of Things (IoT), smart meters, and energy management systems. These systems connect electrical devices to digital networks to automatically and efficiently monitor and control consumption. [12]

### **I.4.1. Definition of smart technologies:**

These are a set of modern technologies that rely on digital systems, sensors, internet connectivity, and data analytics to enable devices and systems to operate more efficiently and intelligently. These technologies allow devices to collect information about their environment, process it, and make decisions or execute commands automatically, without direct human intervention.

Smart technologies are used in many fields, such as energy, home automation, industry, transportation, and smart agriculture, where they help improve performance, reduce resource consumption, and facilitate the management of various systems. [12]

These technologies often rely on several key elements, the most important of which are:

### 1.4.2. Internet of Things (IoT):

The Internet of Things (IoT) is a system that connects physical devices, sensors, and electronic systems via the internet, enabling them to automatically collect, exchange, and analyze data.

One of its most important applications is in the energy sector:

- Monitoring the energy production of solar systems.
- Collecting data on electricity consumption in homes and buildings.
- Remotely controlling electrical appliances.
- Improving energy efficiency and reducing waste.

#### • Smart Meters:

Smart meters are advanced electronic devices that accurately measure electricity consumption in real time and transmit the data directly to the electricity provider or the user. One of their most important features is:

- Real-time recording of energy consumption.
- Automatic data transmission without manual reading.
- Allows users to track their energy consumption.
- Compatible with smart grid management. [13]



**Figure I. 4:**Example of a smart meter for monitoring consumption [13]

### **I.4.3. Energy Management Systems (EMS):**

Energy management systems are software systems that use sensors and communication technologies to monitor energy consumption and analyze data to improve energy efficiency.

One of their most important functions is:

- Real-time monitoring of energy consumption.
- Data analysis to identify sources of waste.
- Intelligent management of electrical appliances.
- Integration of renewable energy sources, such as solar power, into the electrical grid.

The importance of these technologies lies in:

- Improved energy efficiency.
- Reduced costs and electricity consumption.
- Support for the use of renewable energy.
- The development of smart grids. [14]

## **I.5.Existing research**

In the field of solar energy and intelligent energy management systems, numerous studies have been conducted to maximize the exploitation of solar energy, [12] to improve energy efficiency and implement smart technologies such as the Internet of Things (IoT), smart meters, and energy management systems (EMS). Here is a summary of the main findings from previous studies .[14]

### **I.5.1. Solar energy in homes and buildings:**

Messenger and Ventre (2010): Their work focused on the design of residential solar energy systems and their integration into electrical grids, emphasizing the importance of intelligent storage and control to reduce losses and promote the use of renewable energy .[15]

Duffie and Beckman (2013): They studied the thermal engineering of solar energy systems and demonstrated that improving the design of solar panels and storage systems significantly contributes to increasing system productivity and efficiency. [16]

### **I.5.2. Energy Management and Intelligent Control Systems:**

Siano (2014) indicated that the application of smart grids and energy management systems helps to improve the balance between electricity production and consumption, reduce waste, and increase the use of renewable energy.

Gubbi et al. (2013) focused on the role of the Internet of Things (IoT) in monitoring and analyzing energy consumption and explained that connecting smart devices to centralized control systems significantly improves energy efficiency. [17]

### **I.5.3. Smart Meters and Their Role:**

The International Energy Agency (2022) explained that the use of smart meters enables real-time monitoring of consumption and incentivizes consumers to improve their energy use, thereby reducing costs and carbon emissions.

Other studies (IRENA, 2019) have shown that integrating smart meters with energy management systems and renewable energy sources increases the stability of the electricity grid and improves the efficiency of energy distribution. [18]

## **I.6. Problem statement, objectives, methodology**

### **I.6.1. Problem Statement:**

The increasing global demand for electricity, coupled with the environmental impacts of fossil fuel consumption and the depletion of conventional energy resources, has created an urgent need for sustainable and clean energy solutions. Despite its vast solar energy potential, Algeria remains heavily reliant on natural gas for electricity generation. Conventional energy systems also face challenges related to energy efficiency, supply reliability, and environmental pollution. Therefore, there is a need to study and develop gridconnected hybrid photovoltaic systems capable of improving energy reliability, reducing carbon emissions, and promoting the integration of renewable energy into the electricity grid.

**I.6.2. Objectives:**

This study aims to:

- 1 Analyze the performance of grid-connected hybrid photovoltaic systems under different operating conditions.
- 2 Develop mathematical models and simulation models for the components of a photovoltaic system, such as solar panels, batteries, inverters, and the electricity grid.
- 3 Evaluate the impact of climatic factors, including solar radiation and temperature, on system efficiency.
- 4 Comparing different operating scenarios, including grid-connected and battery-powered systems.
- 5 Studying the economic feasibility of hybrid photovoltaic solar energy systems and the benefits of selling surplus energy to the public grid.
- 6 Investigating the role of smart technologies, such as energy management systems, the Internet of Things (IoT), and smart meters, in improving energy management and system performance.
- 7 Highlighting the importance of integrating renewable energy in achieving sustainable development and reducing environmental impacts.

**I.6.3. Methodology:**

The study follows an analytical and simulation-based methodology, which includes the following steps:

1. Conducting a theoretical review of renewable energy technologies, particularly photovoltaic solar energy systems and hybrid energy systems.
2. Collecting climatic and technical data related to solar radiation, temperature, electrical loads, and system components.

3. Designing mathematical models of the photovoltaic solar energy system components.
4. Simulating and analyzing system performance using specialized software such as MATLAB/Simulink and HOMER Pro.

## **I.7. Conclusion:**

Chapter 1 addressed the theoretical framework of solar energy and photovoltaic systems. It discussed the importance of electricity in achieving economic and social development, highlighting the problems associated with traditional energy sources such as fossil fuel depletion and environmental pollution. The concept of solar energy was explained as one of the most important and abundant clean renewable energy sources. The operating principle of photovoltaic cells and the various components of a solar system, such as solar panels, batteries, inverters, and charge controllers, were also explained.

Furthermore, the types of photovoltaic systems were presented, particularly stand-alone, gridconnected, and hybrid systems. The advantages and operational characteristics of each system were highlighted, providing a theoretical foundation for understanding the applied study conducted in subsequent chapters.

## ***Chapter II:***

### ***Modelling and Technical Description***

## II.1. Introduction

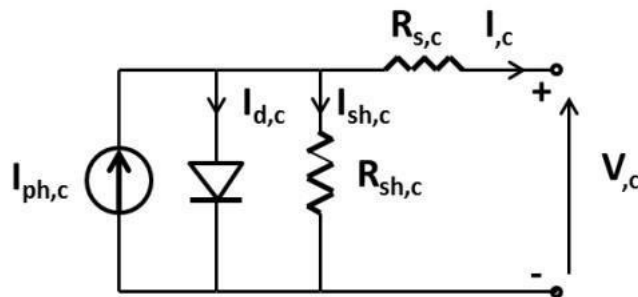
This chapter focuses on the mathematical modelling and technical description of the components of a photovoltaic solar system. It explains the operating principle of a solar cell and the mechanism for converting solar energy into electrical energy. It also covers the equivalent electrical representation of the cell, particularly the single-diode model, which is one of the most widely used models for studying and analyzing the performance of photovoltaic systems.

The chapter also includes a definition of the system's basic components, such as solar panels, storage systems, and inverters, clarifying the role of each element in improving efficiency and ensuring system stability. Furthermore, the impact of climatic factors, especially solar radiation and temperature, on the system's performance and operational behavior is analyzed. Thus, this chapter provides a foundation for understanding the technical aspects of the system, paving the way for performance analysis and results evaluation in subsequent chapters.

## II.2. Photovoltaic Panel Model

### II.2.1. Photovoltaic Cell Model:

Represents the equivalent electrical circuit of a photovoltaic cell, which consists of a current source that expresses the photovoltaic current, a diode, and a resistor in series and another in parallel.



**Figure II. 5:**Modèle électrique d'une cellule PV [19]

According to this electrical model, the current generated in a photovoltaic cell can be described by an equation linking the different factors that influence it.

$$I_c = I_{ph,c} - I_{0,c} \left( \exp \left( \frac{q (V_c + R_{s,c} I_c)}{a K T} \right) - 1 \right) - \frac{V_c + R_{s,c} I_c}{R_{sh,c}} \dots \dots \dots (1)$$

( $I_{ph, c}$ ) represents the photocurrent resulting from solar radiation incident on the cell, while ( $I_{0, c}$ ) represents the reverse saturation current of the diode. The symbols ( $q$ ), ( $a$ ), ( $K$ ), and ( $T$ ) denote the elementary charge, the diode ideality coefficient, the Boltzmann constant, and the cell temperature, respectively. ( $V_c$ ) is the potential across the cell terminals, and ( $I_c$ ) is the current. Furthermore, ( $R_{s, c}$ ) and ( $R_{sh, c}$ ) represent the series and parallel resistances, respectively, two essential elements that affect the behavior and performance of the photovoltaic cell. [19]

### II.2.2. Model of a photovoltaic module:

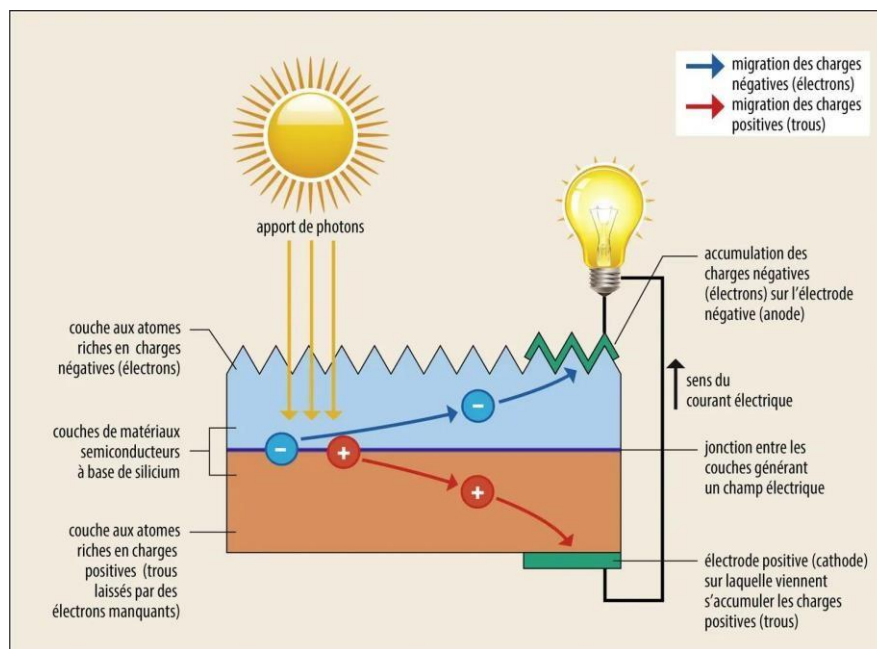
The operating principle of a photovoltaic cell relies on the properties of semiconductors, particularly silicon, which has the ability to convert light energy into electrical energy. When photons, particles carrying solar energy at a speed of approximately 300,000 km/s, strike the surface of the cell, they transfer their energy to the electrons in the silicon atoms, causing their release and the formation of electron-hole pairs.

In the absence of an internal field, the movement of these charges remains disordered and does not allow the generation of a usable electrical current. To overcome this, a PN junction is created by doping the silicon with different elements: the front face is doped with phosphorus to form an electron-rich region (N-type), while the back face is doped with boron to form an electron-deficient region (P-type). This difference generates an internal electric field at the junction.

This electric field ensures the separation of the generated charges: electrons are directed towards the N-type region, while holes migrate towards the P-type region. Through metallic contacts placed on both sides of the cell, these charges are collected and circulated through an external circuit, thus producing a direct current.

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To improve the cell's efficiency, an anti-reflective coating is added to its surface. This reduces photon loss due to reflection and thus increases the amount of light absorbed, thereby improving energy conversion efficiency. [20]

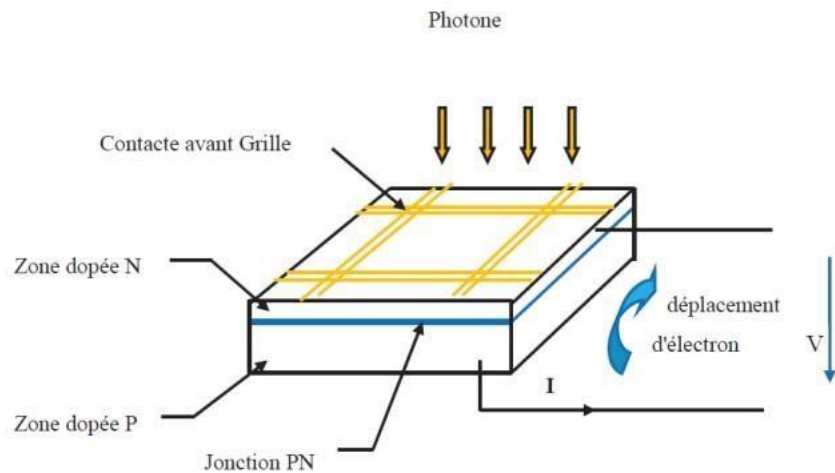


**Figure II. 6:**Operation of the photovoltaic cell with metallic contacts and current flow [21]

### II.2.3. Structure and Working Principle of a PN Junction Photovoltaic Cell

The operating principle of a photovoltaic cell is based on the photoelectric effect, where the sun's light energy is directly converted into electrical energy. This process occurs through the generation and transfer of positive and negative electrical charges within a semiconductor material under the influence of light.

Photovoltaic cells are made from silicon alloys, sliced into thin p-type or n-type layers by adding impurities such as boron or phosphorus. The combination of two regions of different types (p and n) forms a p-n junction, the fundamental element of a solar cell .[21]



**Figure II. 7:** Schematic representation of a PV cell [22]

In this junction, an electric field is generated, separating the positive and negative charges and maintaining their equilibrium. Metallic electrodes, arranged in a grid at the front and back of the cell, collect the resulting electric current.

Thus, a photovoltaic cell is a device capable of converting solar energy into electrical energy, thanks to three main mechanisms:

- Absorption of photons whose energy exceeds the band gap of the material.
- The conversion of photon energy into electrical energy involves the generation of electron-hole pairs within the semiconductor.
- The charges thus produced are then collected in the cell.

Therefore, the material used must possess two energy levels and sufficient conductivity to allow current flow, which explains the widespread use of semiconductors in the manufacture of solar cells. An internal electric field is also necessary to separate the electron-hole pairs, and this is generally achieved using a PN junction. [22]

### II.3. Storage Model (Li-ion/GEL Batteries)

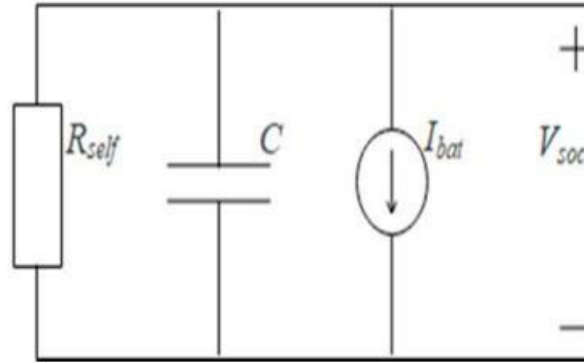
Given the wide variety of battery cell types and the various factors influencing their performance, an experimental model allows for a simplified description of battery behavior.

The most commonly used storage system in photovoltaic solar installations is the lead-acid battery, and numerous models have been proposed to represent its charging processes. [23]

### II.3.1. Battery Energy Storage System (BESS):

Batteries are efficient means of storing electrical energy. They rely on charging chemical cells to store energy, which is then reused when needed through a discharge process. Various types of batteries are used in this field, including nickel-metal hydride (NiMH) batteries, leadacid batteries, redox batteries, lithium-ion (Li-ion) batteries, and sodium sulfur (NaS) batteries.

In this section, we focus on two main types of batteries: Li-ion/GEL Batteries as they are the most widely used in energy storage applications, especially in renewable energy systems such as wind and solar power, due to their efficiency and reliability in storing and reusing energy. [24]



**Figure II. 8:**Battery équivalent circuit [23 or 24]

The differential equation describing the battery self-discharge model is obtained by applying Kirchhoff's Current Law (KCL) at the upper node:

$$C \frac{dV_{soc}(t)}{dt} + \frac{V_{soc}(t)}{R_{self}} + I_{bat}(t) = 0$$

**The equation in canonical form:**

$$\frac{dV_{soc}(t)}{dt} + \frac{1}{R_{self}C} V_{soc}(t) = -\frac{1}{C} I_{bat}(t)$$

$V_{soc}$  : Voltage across the circuit terminals representing the state of charge (State of Charge, SoC).

$C$  : Main capacity storing the battery's energy.

$R_{self}$  : Self-discharge resistance (represents energy losses at open circuit).

$I_{bat}$  : Battery current (leaving the circuit in the direction of the arrow).

### II.3.2. Storage Model (Li-ion Batteries):

A lithium-ion (Li-ion) battery is an advanced energy storage technology that uses lithium ions as the key component of its electrochemistry.

#### 1. Operating Principle:

- During a discharge cycle, the lithium atoms in the anode are ionized and stripped of their electrons.
- The lithium ions ( $Li^+$ ) pass through the electrolyte and reach the cathode, where they recombine with their electrons and become electrically neutralized.
- Lithium ions are small enough to pass through a micro-permeable separator between the anode and cathode.
- This small size of lithium (second only to hydrogen and helium) allows Li-ion batteries to produce high voltage and significant charge storage per unit mass and volume. [23]

#### 2. Materials Used:

Li-ion batteries can use different materials for the electrodes:

Most common cathode: oxide of cobalt and lithium ( $LiCoO_2$ )

- Anode: graphite (carbonic) Other cathode materials:
- Lithium manganese oxide (used in hybrid and electric vehicles)
- Lithium iron phosphate

The electrolyte is generally composed of ethers, a class of organic compounds, which allows the circulation of lithium ions. [22]

### 3. Intercalation:

- The cathode contains metallic lithium combined with oxides (such as  $\text{LiCoO}_2$ ), providing lithium ions.
- The anode contains lithium carbon.
- These materials enable the phenomenon of intercalation, that is, the insertion or removal of lithium ions between the electrode structures, which is essential for charge and discharge cycles.

## II.4. Inverter and Converters

### II.4.1. Inverter:

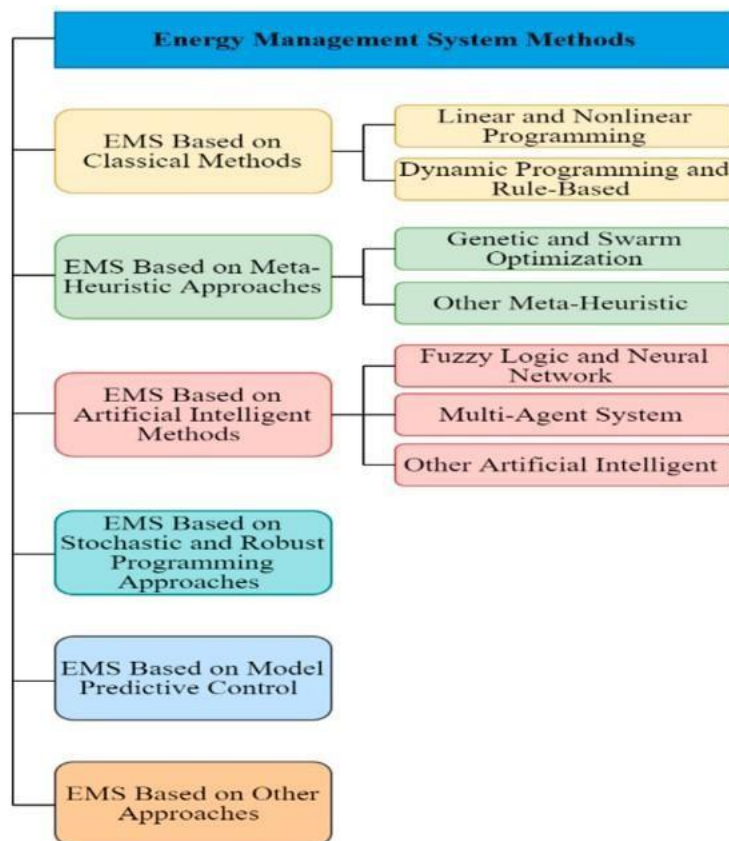
For efficient use of batteries in home systems, an inverter is an essential component. It is installed after the battery to connect it to electrical appliances or the grid. Since the battery produces direct current (DC), the inverter converts it to alternating current (AC), a form suitable for powering most household appliances, and also allows energy to be fed back into the electrical grid.

The inverter's role is not limited to conversion; it performs other important functions. In the absence of a battery, it can serve as a direct intermediary between the solar panels and the grid, thus ensuring maximum power point tracking (MPPT) to optimize energy production. It also synchronizes the produced current with the voltage and frequency characteristics of the grid to guarantee safe and stable operation. Furthermore, it protects the system by automatically disconnecting in the event of disturbances such as voltage drops, and it records operating data to monitor performance and facilitate maintenance.

However, the inverter must be chosen according to the system specifications, as it operates within specific limits regarding power, voltage, and current. Despite its high efficiency, the inverter is not a perfect device; its efficiency in modern systems is approximately 95 %.[25]

## II.5. Intelligent Energy Management System (EMS)

An Energy Management System (EMS) is an advanced computer system used to monitor and control the production, transmission, distribution, and consumption of energy within electrical networks, particularly in smart grids and microgrids. This system aims to achieve optimal operation by improving efficiency, reducing costs, and ensuring the stability and security of the electrical system. [26].



**Figure II. 9:**Methods and techniques of Energy Management Systems (EMS) [26]

### II.5.1. Objectives and Functions of an EMS System:

The primary objective of an EMS system is to achieve an efficient balance between energy supply and demand, while minimizing operating costs even under uncertainties such as:

- Fluctuations in renewable energy production.
- Changes in electricity prices.
- Variable load consumption patterns.

The system also provides additional functions such as:

- Power scheduling.
- Real-time operation control.
- Network security management. [27]

With the evolution of networks and the integration of new technologies such as:

- Electric vehicles (PEVs).
- Storage systems (ESS).
- Renewable energy (RESs).

EMS design has become more complex, especially with the integration of technologies such as:

- Internet of Things (IoT).
- Machine learning (ML) [27]

## **II.6. Operating conditions of a grid-connected photovoltaic system**

A grid-connected photovoltaic system operates in a series of operating modes that vary depending on solar irradiance, battery status, and electricity demand.

The control system aims to balance production and consumption and ensure a continuous power supply with the highest possible efficiency.

In this study, the operating modes were divided into three main scenarios, as illustrated in the simulation results. [28]

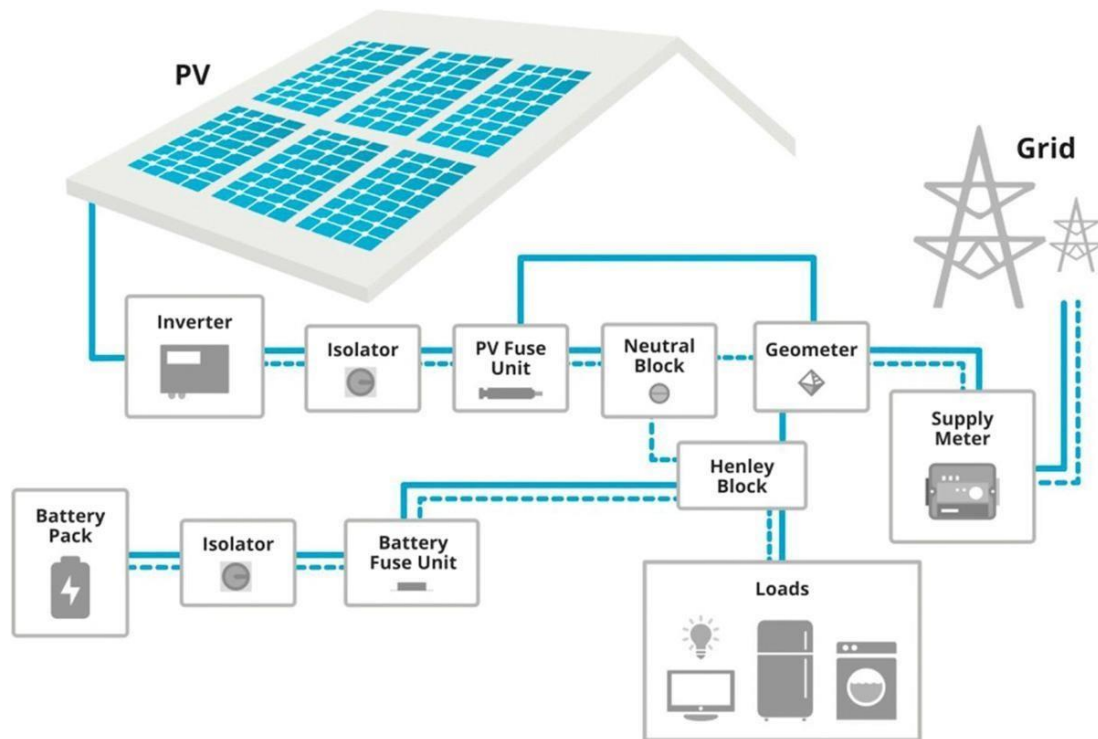
### **II.6.1. Scenario 1: System Operation with Solar Power and a Charged Battery:**

#### **a) Scenario Definition:**

This scenario represents the ideal operating condition for a photovoltaic system. Solar radiation is sufficient to power the solar panels efficiently, allowing for continuous electricity generation. The battery is also in a sufficiently charged state to support the system when needed and ensure a stable power supply.

**b) Power Flow in this Scenario:**

In this scenario, the solar panels generate electricity as direct current (DC), which is converted by the inverter into usable alternating current (AC). This power is distributed gradually according to priority: first, it is used to power electrical loads; then, if there is a surplus, it is used to charge the battery. If production exceeds demand, the excess power is exported to the electrical grid. [29]



**Figure II . 10:**Electrical wiring diagram and safety and protection elements for a hybrid solar power system [29]

**c) Battery Behavior:**

In this scenario, the battery is at a high or near-full charge, making its role secondary in operation. It is only used in cases of fluctuating production or sudden increases in energy demand. Consequently, it is not subject to significant discharge during this scenario.

**d) Operating Characteristics:**

In this scenario, the system operates at its highest efficiency, fully utilizing solar energy, significantly reducing reliance on the electrical grid, minimizing energy losses, and achieving greater stability in overall system performance.

**e) Importance of the Scenario:**

This scenario is considered the ideal model for operating photovoltaic systems because it allows for partial or complete energy independence, contributes to reducing electricity consumption costs, increases the overall system efficiency, and optimizes the utilization of available resources. [29]

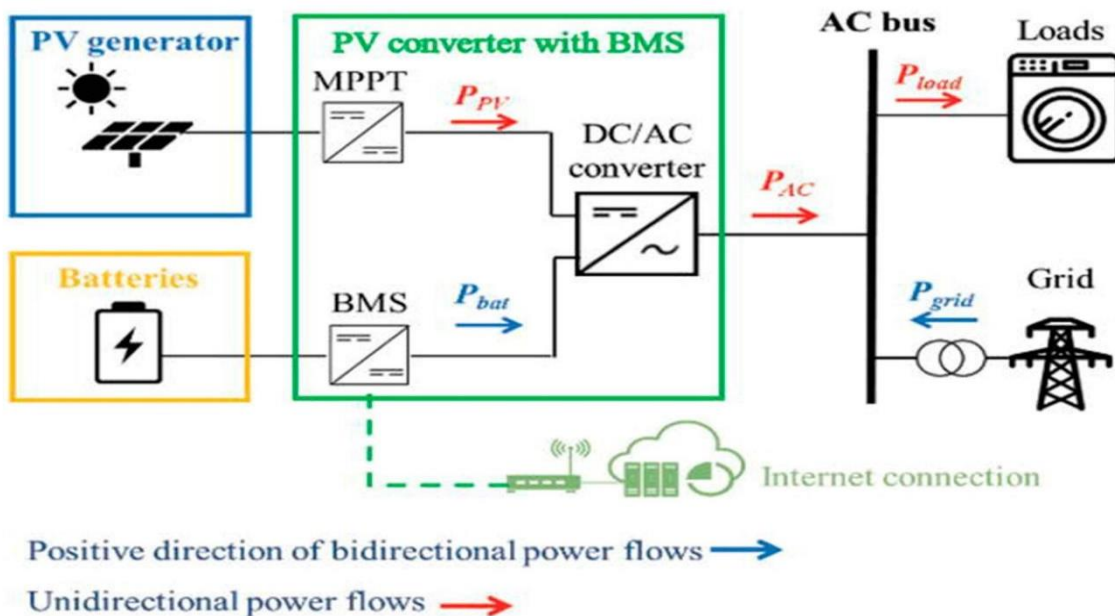
**II.6.2. Scenario 2: System Operation with Solar Power and a Depleted Battery:**

**a) Scenario Definition:**

This scenario represents an operating condition where the photovoltaic system is able to generate electricity thanks to available solar radiation. However, the battery is discharged or has a low charge level, limiting its ability to support the system or contribute effectively to powering electrical loads.

**b) Power Flow in this Scenario:**

In this mode, the solar panels generate electricity, which is converted by the inverter into usable alternating current (AC). The generated power is initially directed to power the electrical load, and any surplus is used to recharge the battery. When the solar power generated is insufficient to meet demand, the electrical grid is used to cover the shortfall and ensure a continuous power supply. [30]



**Figure II . 11:Grid-Tied Hybrid Solar PV System with Battery Storage [30]**

**c) Battery Behavior:**

In this scenario, the battery has a low charge level, so greater attention is paid to recharging it when there is a surplus of solar energy. Due to the low charge level, its contribution to powering the load is limited or almost nonexistent, increasing reliance on the electrical grid.

**d) Operating Characteristics:**

The system operates in this case as a hybrid system, utilizing both solar and electrical grid power. Moderate grid dependence is observed due to the low storage capacity, while load power remains relatively stable thanks to the integration of the different energy sources. Furthermore, power flow is directly affected by variations in solar irradiance intensity during operating periods. [30]

**e) Significance of the Case:**

The significance of this case lies in highlighting the crucial role of the electrical grid as a backup power source when storage capacity is low. It also helps to illustrate the importance of battery capacity in improving system stability and ensuring continuous power supply. This case also contributes to studying the effect of complete battery discharge on the overall performance and efficiency of the photovoltaic system. [30]

### **II.6.3. Scenario3: Third Scenario: Absence of Solar Power with an Inefficient Battery**

**a) Scenario Definition:**

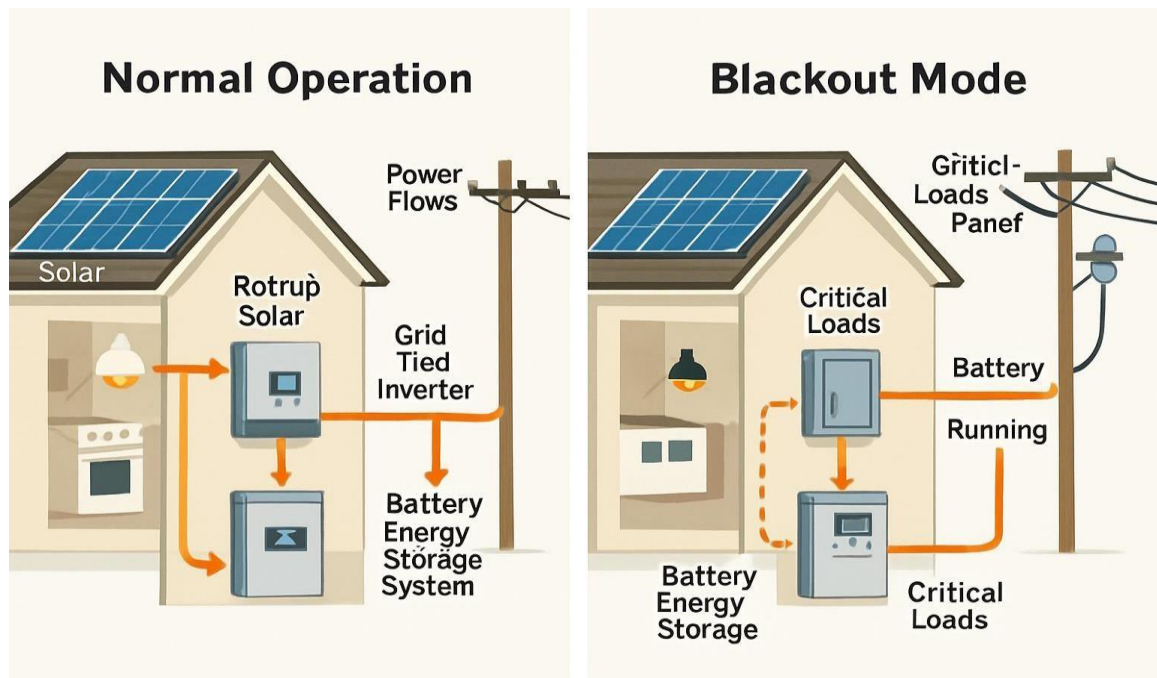
This scenario represents the most challenging operating conditions for a photovoltaic system. The solar panels produce no electricity or very little due to the absence of solar radiation or adverse weather conditions. Simultaneously, the battery is unable to supply the system with power due to complete discharge or low charge level. In this situation, the system becomes entirely dependent on the conventional electrical grid to ensure a continuous and uninterrupted power supply to electrical loads.

**b) Causes of the Scenario:**

This scenario occurs due to a combination of natural and technical factors that directly affect the performance of the solar system. Among the most important of these factors are the absence

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of sunlight during the night or reduced radiation intensity due to heavy cloud cover and rain. A decrease in the angle of incidence of solar radiation can also lead to a reduction in the amount of power produced by the photovoltaic panels. Furthermore, a completely discharged battery or a decrease in its storage capacity renders it unable to support the electrical load when needed. [31]



c) **Power Flow in this Scenario** Figure II. 12: Normal Operation vs Blackout Mode [31]

In this scenario, the contribution of solar panels is almost negligible, as they do not produce enough electricity to power the loads. The battery is also inefficient and cannot provide the stored energy needed to support the system. Therefore, the entire power supply is diverted to the electrical grid, which becomes the sole source responsible for supplying the loads with electricity and ensuring stable operation.

**d) System Behavior:**

In this scenario, the system relies entirely on the electrical grid to meet its energy demands, with a temporary interruption in the contribution of renewable energy sources. Despite the absence of solar energy production and the inefficiency of the battery, the power supply remains stable thanks to the electrical grid's ability to maintain stable voltage and frequency, ensuring the continued normal operation of the electrical loads.

**e) Operating Characteristics:**

- f) This scenario is characterized by several important operating features, most notably the complete reliance on the electrical grid as the sole power source. The contribution of solar energy drops to almost zero, leading to increased consumption of conventional energy supplied from the grid. Despite this, the system remains stable in terms of power supply thanks to the continuous support provided by the grid. [31]

**g) Case Study Importance:**

This case study highlights the importance of a reliable electrical grid to support photovoltaic systems in harsh climatic conditions or during periods of low solar radiation. It also demonstrates the need to increase battery capacity and improve storage systems to enhance system autonomy and reduce reliance on the electrical grid. Furthermore, studying this case study helps in understanding the performance limitations of solar systems and evaluating their operational efficiency under adverse conditions. [31]

## **II.7. System Operation Principle:**

The operation of a photovoltaic system relies on a series of integrated stages to ensure a continuous and efficient supply of electricity. Initially, solar panels convert solar energy into direct current (DC) electricity. Next, an inverter converts this DC to alternating current (AC) suitable for powering various electrical loads.

When there is a surplus of energy produced, it is stored in batteries for later use or fed into the electrical grid, depending on the system's specifications. In cases of low or no solar panel output, such as during nighttime or adverse weather conditions, the electrical load is supplied with the energy stored in the batteries. If this is insufficient, the system relies on the electrical grid to ensure a continuous power supply.

### **II.7.1. Comparative Analysis of Operating Cases:**

**a) Comparison of Power Output:**

The amount of power produced varies depending on the system's operating state. In the first case, solar panel output is high and the battery is fully charged, significantly reducing the need for the electrical grid. In the second case, solar power output is average with a depleted battery, so the system partially relies on the grid to cover the power shortfall. In the third case, solar

panel output is almost non-existent and the battery is ineffective, resulting in complete reliance on the electrical grid to power the loads. [32]

#### **b) Grid Reliance Comparison:**

The level of grid dependence varies depending on the availability of solar energy and the battery's condition. In the first scenario, grid dependence is very low due to sufficient solar power and a fully charged battery. In the second scenario, grid dependence is moderate due to limited battery support. In the third scenario, the system becomes entirely dependent on the grid due to the absence of solar power and no stored battery energy.

#### **c) System Efficiency Comparison:**

The first scenario is the most efficient, as it maximizes solar energy utilization while minimizing conventional energy consumption. The second scenario is moderately efficient due to the reduced battery contribution and partial reliance on the grid. The third scenario is the least efficient, as it lacks any contribution from renewable sources and relies entirely on conventional energy supplied by the grid.

### **II.7.2. General Conclusion on Operating Modes:**

Through studying and analyzing the various operating conditions of a grid-connected photovoltaic system, it becomes clear that the system's performance is directly related to several key factors that affect its efficiency and operational stability. The availability of solar radiation is the primary factor determining the amount of energy produced by the photovoltaic panels. Higher radiation intensity improves production and reduces the need for conventional energy sources, while lower intensity reduces the solar system's contribution to powering the loads.

The battery's charge level also plays a crucial role in ensuring continuous power supply. A fully charged battery allows for the storage of excess solar energy and its use during periods of low production or at night, thus increasing the system's independence and reducing reliance on the electrical grid. Conversely, a discharged battery or low battery capacity increases the need for power from the grid.

Furthermore, the electrical grid is a fundamental element for ensuring system stability, as it compensates for power shortages when solar production is absent or the battery does not have

sufficient charge. Therefore, integrating solar panels with batteries and the electrical grid contributes to improving system efficiency and achieving a better balance between renewable and traditional energy sources. [32]

## **II.8. Conclusion:**

Chapter 2 was dedicated to introducing the hybrid photovoltaic system under study, explaining its basic components and how it works. The HOMER Pro simulation software, used in the design and analysis of hybrid energy systems, was introduced, along with an explanation of how to input data related to electrical loads, solar irradiance, component prices, and grid characteristics.

- Various operational scenarios for the system were presented, including:
- Solar system with batteries and grid connection.
- Solar system with grid connection only.
- Solar system with grid connection and surplus energy sales.
- Hybrid systems with storage.

This study highlighted the role of each component within the system and its impact on energy and economic performance, in addition to identifying the best possible configurations in terms of efficiency, cost reduction, and reliability.

# ***Chapter III:***

## ***Simulation and résultats***

### **III.1. Introduction:**

The analysis and simulation of hybrid photovoltaic systems constitute a crucial step in evaluating their technical and economic performance before implementation. Using HOMER Pro software, this chapter examines several grid-connected solar system scenarios, including battery storage and surplus energy sales, in order to identify the most efficient and suitable system in terms of energy production, cost, and profitability.

This chapter presents the simulation results for each system by analyzing energy flows, the percentage of renewable energy utilized, electricity production costs, and the payback period. It also provides a detailed comparison of the different case studies to determine the optimal technical and economic solution under Algerian operating conditions.

### **III.2. Simulation Environment and System Settings**

#### **III.2.1. Definition of a Simulation Environment:**

A simulation environment is a set of software and digital tools used to design a photovoltaic system and study its performance virtually before its actual implementation. This environment allows for the modelling of the system's various components and the analysis of their behavior under diverse operating conditions.

The importance of simulation lies in its ability to predict system efficiency, evaluate energy production, identify potential weaknesses, and improve design while minimizing errors, all without the need to build a costly or experimental real system.

#### **III.2.2. How a Simulation Environment Works:**

The simulation environment works by inputting data about the photovoltaic system, such as the characteristics of the solar panels, inverter, batteries, and site conditions (solar irradiance and temperature). The software then performs mathematical calculations and models of the system's behavior under different conditions.

The energy production and distribution between the electrical load, battery storage, or export to the grid are then simulated. Finally, the results are presented in tables and graphs, which help analyze performance, evaluate system efficiency, and optimize it before actual implementation.

[33]

### **III.2.3. Simulation Environment:**

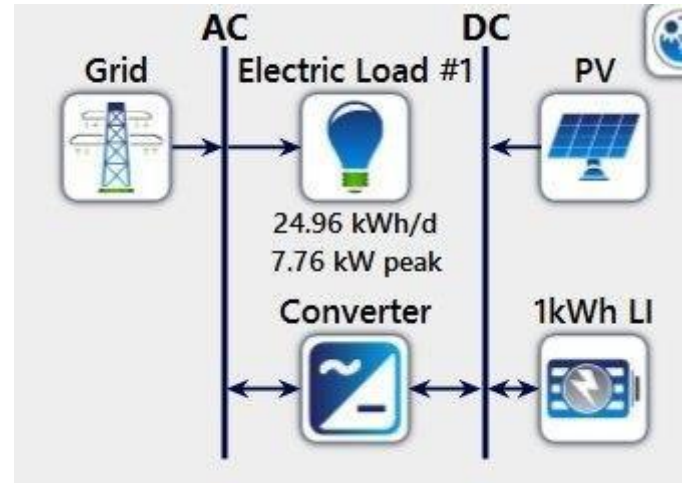
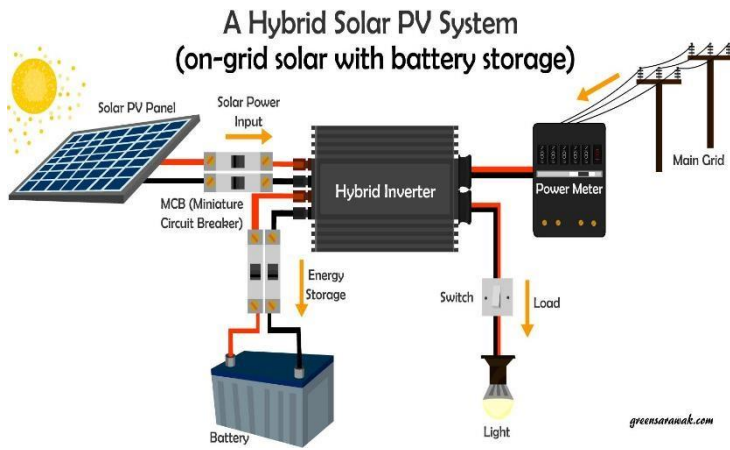
This study utilized MATLAB Simulink software to simulate a grid-connected photovoltaic system. This software is among the most important in the renewable energy field, enabling the modelling of energy systems and the highly accurate analysis of the behavior of their various components.

The software also allows for the study of energy flow between the solar panels, the battery, the electrical load, and the electrical grid, facilitating the evaluation of system performance under different operating conditions. Furthermore, the software offers a range of important features that simplify the analysis and simulation process, most notably:

- Simulating the actual performance of the photovoltaic system.
- Analyzing the amount of electrical energy produced by the solar panels.
- Studying the electrical load's consumption and its variation over time.
- Evaluating the energy exchange process between the electrical grid, the battery, and the solar system.
- Monitoring system stability and optimizing its operational efficiency.
- The ability to test system performance under different climatic conditions, such as variations in solar irradiance and temperature. [33]

### **III.3. System Setup:**

The system under study consists of a grid-connected photovoltaic (PV) system, designed to generate electricity from solar energy with the capability for continuous power exchange with the electrical grid. This system includes a set of essential components that work together to ensure operational efficiency and system stability.



**Figure III. 13:**Hybrid Solar Power System [38]

### III.3.1. The Electrical Grid:

The electrical grid is the fundamental element of the system. It ensures the supply of power to the electrical load when the solar system's output is low, and it receives excess power generated by increased photovoltaic panel output. This connection allows for continuous power supply and improves the stability of the energy system. [34]

### III.3.2. Photovoltaic Panels (PV):

The function of photovoltaic panels is to convert solar energy into electrical energy in the form of direct current (DC), based on the photovoltaic effect. These panels are the primary source of energy production within the system.

#### ➤ Specifications adopted in this study:

- Panel type: Monocrystalline.
- Rated power: 465Wh
- Output type: Direct current (DC).
- Efficiency: Between 18% and 20%. [35]

### III.3.3. Inverter:

An inverter converts the direct current (DC) generated by solar panels or a battery into alternating current (AC) to power electrical loads and connect the system to the electrical grid. A bidirectional inverter also allows for reverse conversion when energy is needed to store or share power with the grid. [36]

➤ **Specifications:**

- Type: Bidirectional inverter.
- Efficiency: Approximately 95%.
- Conversion Function: DC/AC and AC/DC.

### **III.3.4. Electrical Load:**

The electrical load represents the daily energy consumption within the system and reflects the user's electricity needs during different operating periods.

- System Data:
- Daily Energy Consumption: 24.96 kWh/day.
- Maximum Power: 7.76 kW.

### **III.3.5. Battery (Battery Storage):**

The battery is used to store excess electrical energy produced by solar panels for use at night or during periods of low solar irradiance. This contributes to system stability and reduces reliance on the electrical grid.

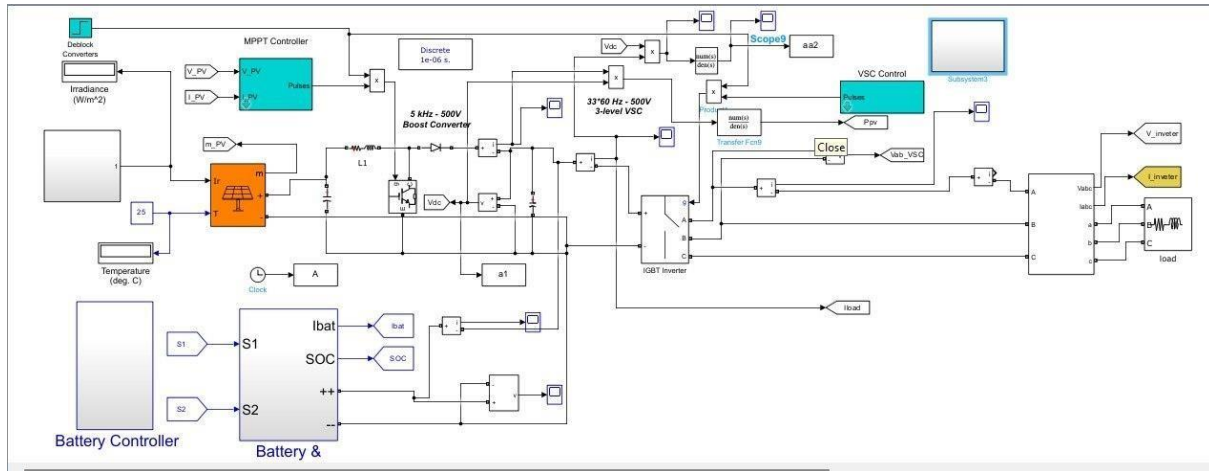
**Default Specifications:**

- Type: Lithium-ion (Li-Ion) battery.
- Capacity: 24 KWh
- Rated Voltage: DC compatible.
- Function: Energy storage and backup power supply. [36]

## **III.4. Explanation of the photovoltaic system diagram:**

This diagram represents a simulation model of a hybrid photovoltaic system designed using MATLAB Simulink software. Its purpose is to study how electrical energy is transferred between the various components of the system: the solar panels, battery, inverter, electrical grid, and electrical load.

This model also allows for the analysis of system performance under different operating conditions, such as high or low solar irradiance, as well as monitoring voltage, current, and power values within the system. This helps in accurately understanding how the system works and improving its operational efficiency.



**Figure III. 14:**Simulation diagram of a renewable energy system using Simulink software (PV) System:

The photovoltaic (PV) system is the primary source of electrical power within the system, converting solar energy into direct current (DC) electricity. This stage is fundamental, and the rest of the system relies on it to generate power and supply electrical loads.

The amount of energy produced by the panels depends on several important factors, most notably the intensity of solar radiation and the ambient temperature. Therefore, the production capacity varies continuously depending on climatic conditions. The higher the intensity of solar radiation, the higher the electrical power produced by the panels.

Within the diagram, several electrical variables related to the solar panels are measured:

- Phase voltage ( $V_{pv}$ ).
- Output current ( $I_{pv}$ ).
- Output power ( $P_{pv}$ ).

These measurements are used to monitor system performance and control the flow of energy to the other components of the system.

When sunlight is available, the panels generate electrical energy, which is then sent directly to a DC-DC converter to regulate the voltage before being distributed to the electrical load, battery, or the electrical grid.

### III.4.1. Battery (Battery Storage):

The battery is one of the most important components of a hybrid photovoltaic system, as it serves as the electrical energy storage unit within the system. Its primary function is to store excess energy generated by the solar panels and utilize it when solar radiation is low or absent.

The battery helps improve system stability and ensures a continuous power supply, especially at night or during periods of low solar output.

The battery operates in two basic states: **A)**

#### **Charging State:**

This occurs when the energy produced by the solar panels exceeds the energy required by the electrical load. The excess energy is then directed to the battery for storage and later use.

#### **B) Discharging State:**

This occurs when the load's energy consumption exceeds the power produced by the solar panels. The battery then supplies the system with electrical energy to compensate for the shortfall.

A number of battery variables are monitored, such as:

- Battery Voltage ( $V_{bat}$ ).
- Charging and Discharging Current ( $I_{bat}$ ).

Status of Charge (SOC). These measurements help determine the energy level stored in the battery and control the charging and discharging process safely and efficiently.

### III.4.2. DC-DC Converter:

The DC-DC converter is a fundamental component of the photovoltaic system. Its primary function is to regulate the voltage generated by the solar panels or battery before it is sent to the inverter or other system components.

This converter raises or lowers the voltage according to operating requirements, thus improving power transmission efficiency and reducing electrical losses within the system.

The converter also helps stabilize the voltage and maintain system stability, especially when operating conditions change or the power output from the solar panels fluctuates.

The converter's operation relies on electronic control signals generated by the control system. One of the most important technologies is PWM, which controls the switching speed and the output voltage of the converter.

### **III.4.3. Inverter:**

The inverter converts the direct current (DC) generated by the solar panels or battery into alternating current (AC), as most electrical loads and power grids operate on AC.

The inverter is considered one of the most important components of the system because it connects the DC and AC components within the system.

The inverter performs several important functions, including:

- Supplying power to electrical loads.
- Connecting the system to the electrical grid.
- Regulating power flow within the system.
- Maintaining voltage and frequency stability.

A range of values related to the inverter are measured within the diagram, such as:

- Output AC voltage ( $V_{ac}$ ).
- Alternating current ( $I_{ac}$ ).
- Frequency (Freq).

These measurements help ensure the quality of the electrical power produced and the stability of the operation.

### **III.4.5. Control System:**

The control system is the brain of the photovoltaic system, as it is responsible for managing and operating the various components of the system in a coordinated and efficient manner.

The control system monitors the voltage, current, and power within the system, then sends appropriate control signals to the transformers, inverter, and battery to ensure optimal performance.

The most important functions of the control system include:

- Regulating the electrical voltage.
- Controlling battery charging and discharging.
- Monitoring power flow. Protecting the system from disturbances and malfunctions.
- Improving operational efficiency.

The control system relies on a set of mathematical and logical blocks within the circuit diagram, which perform calculations and comparisons between reference values and measured real-world values.

The system also utilizes PWM technology to control electronic switches and regulate the electrical power conversion process within the system.

#### **III.4.6. Measurement and Monitoring Units:**

Measurement and monitoring units are used to continuously monitor all electrical variables within the system during the simulation process.

These measurements include:

- Voltage. □ Current.
- Power.
- Battery charge status.
- Frequency values.

The importance of these units lies in their ability to analyze system performance and detect any disturbances or errors that may occur during operation.

The measurement results also help in evaluating system efficiency and improving the control strategies used within the system.

### **III.4.7. Electrical Load and the Electrical Grid:**

The electrical load represents the various devices and equipment that consume the electrical power generated by the photovoltaic system.

The electrical grid acts as a backup power source, stepping in when solar panel output drops or when the battery is depleted and unable to supply the electrical load.

In some operating conditions, the system can send excess power to the electrical grid, particularly during peak hours.

When solar panel output exceeds load consumption, the system's operation is crucial.

This connection between the photovoltaic system and the electrical grid helps achieve greater stability in electricity supply and reduces outages.

### **III.4.8. How a Photovoltaic System Works:**

The system's operation depends on the flow of energy between its various components, depending on operating conditions and solar irradiance.

When solar irradiance is present:

The solar panels generate electricity, which is then sent to a DC-DC converter to regulate the voltage. An inverter then converts the energy into alternating current (AC) to power the electrical load.

If there is excess energy, it is directed to the battery for storage or fed into the electrical grid.

When solar irradiance is low:

The solar panels' output decreases, and the battery begins to compensate for the shortfall and supply the load with the necessary electricity.

If the battery's capacity is insufficient, the electrical grid intervenes to cover the deficit and ensure a continuous power supply.

When solar irradiance is absent:

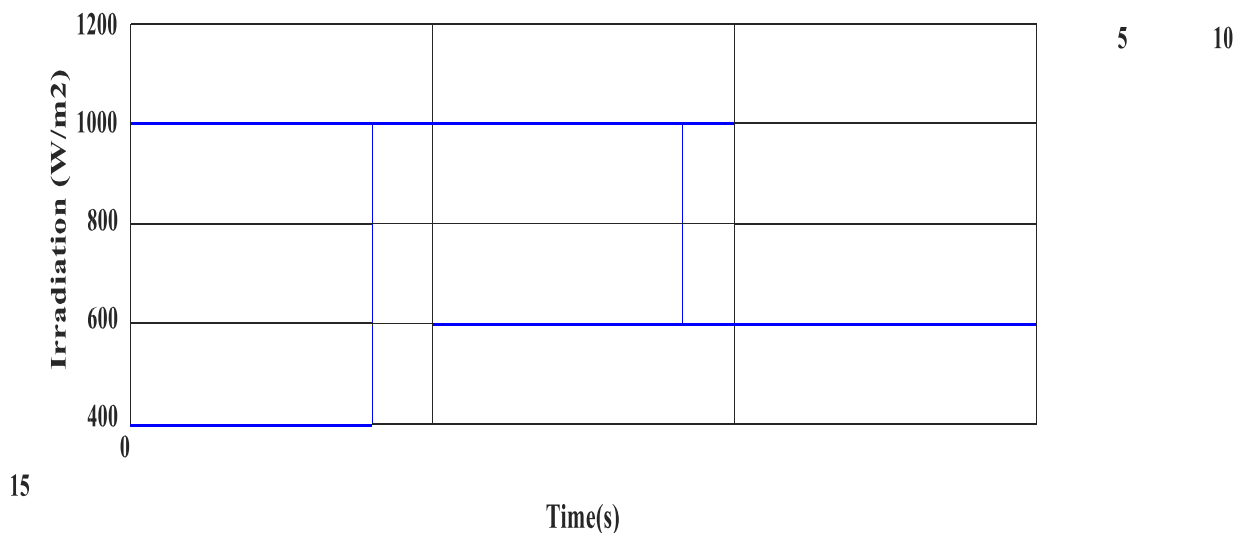
The solar panels cease generating electricity, so the system relies primarily on the battery or the electrical grid to power the load.

In this case, the system switches to a backup operating mode in order to maintain the stability of the electrical supply.

### III.5. Simulation results and analysis of photovoltaic system diagrams

#### III.5.1. Solar irradiance diagram:

This curve represents the change in solar irradiance intensity over time, illustrating the effect of this change on the performance of a photovoltaic system. Initially, during the period from 0 to 4 seconds, the irradiance value is low at approximately 400 W/m<sup>2</sup>, resulting in low power output from the solar panels. Then, between 4 and 9 seconds, the solar irradiance increases to approximately 1000 W/m<sup>2</sup>, significantly increasing power output. After 9 seconds, the irradiance drops to around 600 W/m<sup>2</sup>, causing a slight decrease in power output compared to the previous period. From this curve, it can be concluded that the output of a photovoltaic system is directly related to the value of solar irradiance; the system's efficiency improves with increasing irradiance and decreases with decreasing irradiance.



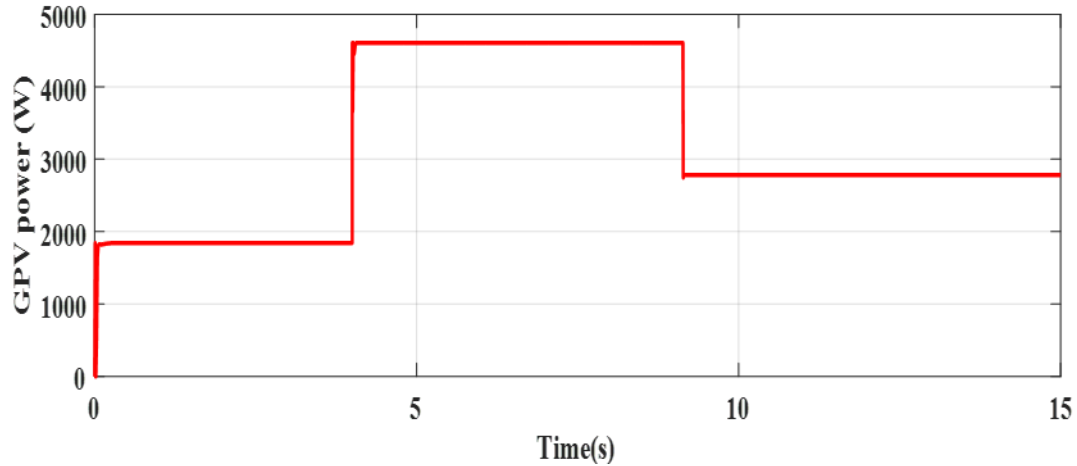
**FigureIII. 15:**Changes in solar radiation

#### III.5.2. PV Solar Panel Power Capacity Curve:

This curve illustrates the evolution of electrical power produced by solar panels as solar irradiance changes. When irradiance is low, power production is weak due to the reduced solar energy reaching the panels. As irradiance increases, electrical power rises significantly, reaching a peak value, reflecting improved performance and increased efficiency of the

## 45

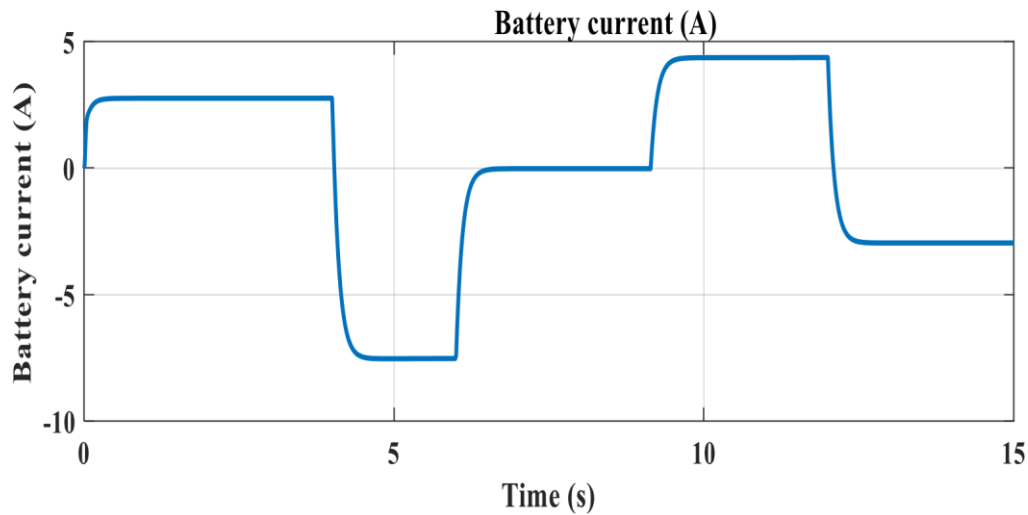
photovoltaic system. After irradiance decreases again, power production gradually declines. These results demonstrate a direct correlation between solar irradiance intensity and electrical power production; increased irradiance leads to increased energy output from solar panels.



**Figure III. 16:**Change in power output from the photovoltaic generator

### III.5.3. Battery Current Curve:

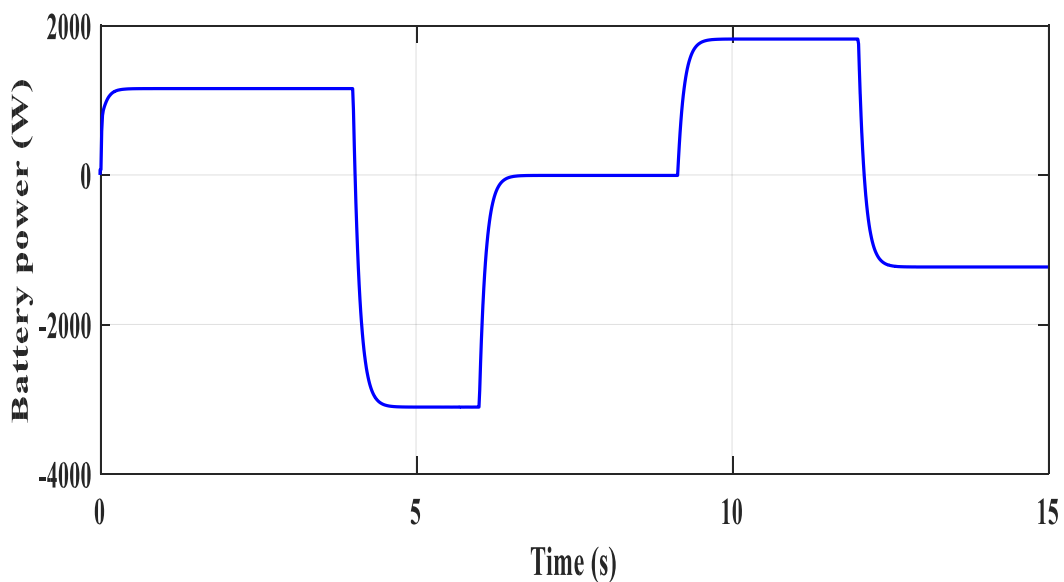
This diagram illustrates the charging and discharging state of a battery within a photovoltaic system, showing the direction of current flow and the battery's role in ensuring stable power supply. A positive (+) current indicates that the battery is charging due to excess energy produced by the solar panels. Conversely, a negative (-) current indicates that the battery is discharging to supply power to the electrical load when solar output decreases. Analysis of the diagram reveals that when solar panel output is high, some energy is directed to charging the battery, while when solar output is low, the battery steps in to compensate for the shortfall and ensure continuous power supply. Therefore, it is clear that the battery plays a crucial role in stabilizing the photovoltaic system and improving the continuity of electricity supply to the loads.



**Figure III.17:**Battery current change

#### III.5.4. Battery Power curve:

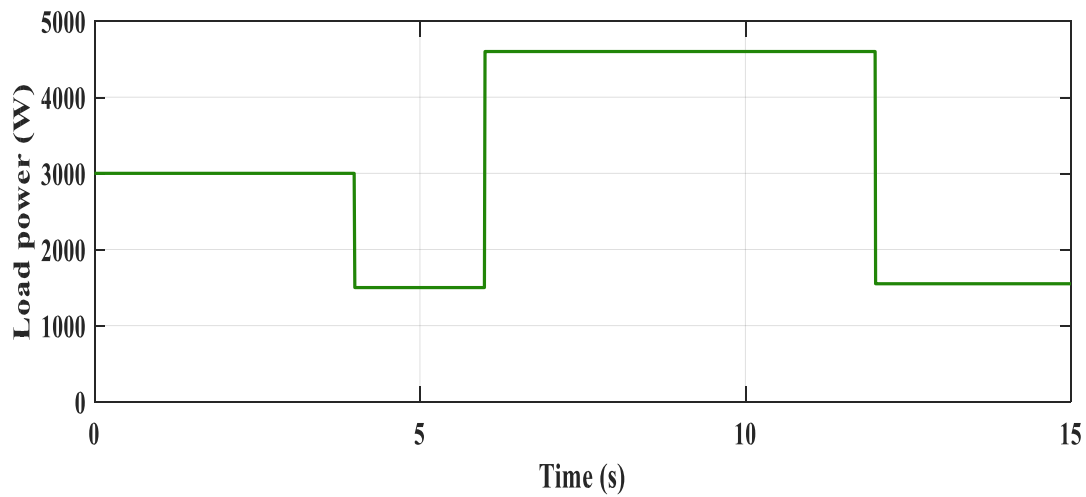
This curve illustrates the power exchange between the battery and the photovoltaic system, reflecting charging and discharging states under different operating conditions. When the power is positive, it indicates that the battery is charging due to excess energy produced by the solar panels. Conversely, when the power is negative, the battery is supplying the electrical load to compensate for insufficient solar output. The battery's power continuously changes in response to variations in solar irradiance and electrical load, highlighting its crucial role in maintaining energy balance within the system and ensuring a stable and continuous power supply.



**Figure III. 18:**Battery current change

### III.5.5. Load Power Curve:

This curve represents the change in electrical load consumption over time, illustrating the varying demand for electricity during different operating periods. We observe that the load is low during certain periods, then gradually rises to a higher value due to increased energy consumption, before decreasing again. This fluctuation directly impacts the performance of the photovoltaic system. When the load increases, the system needs to provide more electrical power to meet the demand. If the power produced by the solar panels is insufficient, the battery or the electrical grid intervenes to supply the load with the necessary power and ensure a continuous, uninterrupted electricity supply.



**Figure III. 19:**Change in load capacity

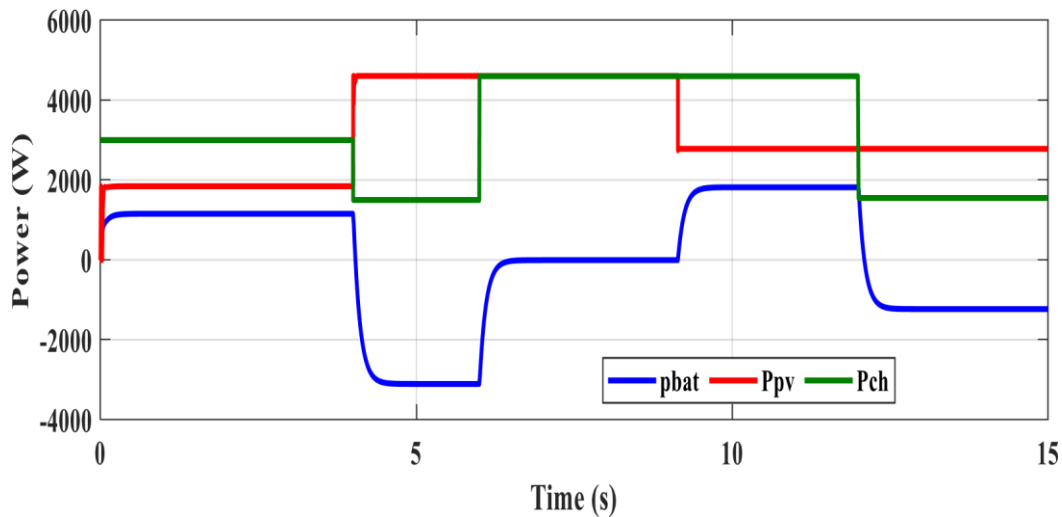
### III.5.6. Power balance curve ( $P_{load} - P_{pv} - P_{bat}$ ):

This diagram represents the power balance within a photovoltaic system. It combines the solar panel power ( $P_v$ ), load power ( $P_{ch}$ ), and battery power ( $P_{bat}$ ) into a single curve, allowing for the analysis of how energy is distributed and exchanged among the various system components during operation. The red curve shows the power produced by the solar panels, the green curve represents the load power, and the blue curve represents the battery's capacity, both in its charging and discharging states.

By analyzing the diagram, we observe that when the solar panel power exceeds the load power, the load is fully supplied with power, while the excess is used to charge the battery, as indicated by the battery's positive capacity. During periods when the electrical load exceeds the panel power, the battery intervenes to cover the deficit and provide the necessary additional

power, as shown by the battery's negative capacity, indicating its discharge state. In certain situations, particularly when solar irradiance is low and the battery charge level drops, reliance on the electrical grid becomes essential to ensure a continuous power supply and prevent power outages.

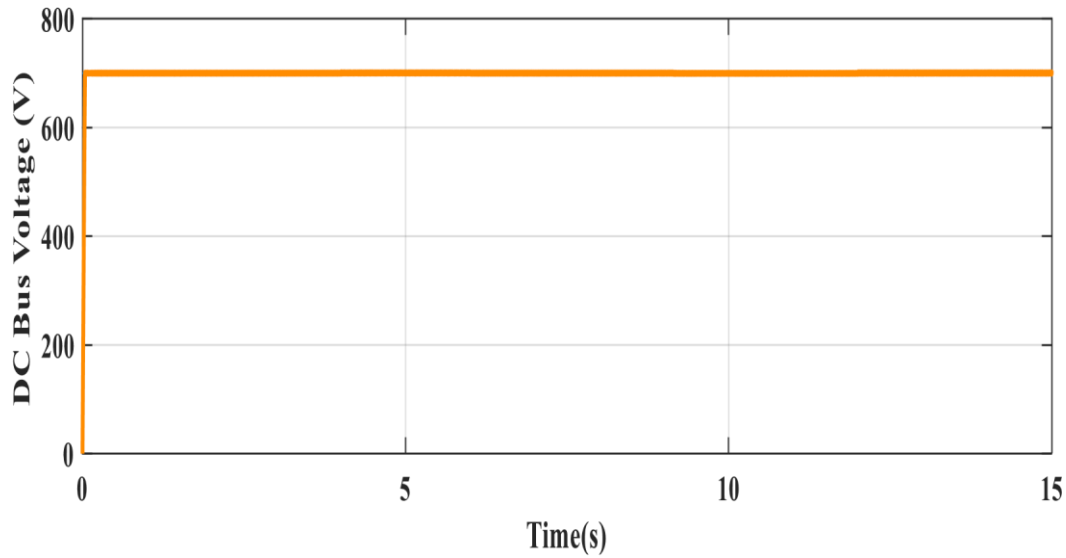
Therefore, this diagram highlights the complementary role between solar panels, the battery, and the electrical grid in achieving power balance within the system and ensuring its stable operation under various operating conditions.



**Figure III.20:**Comprehensive power balance analysis

### III.5.7. DC Bus Voltage Curve:

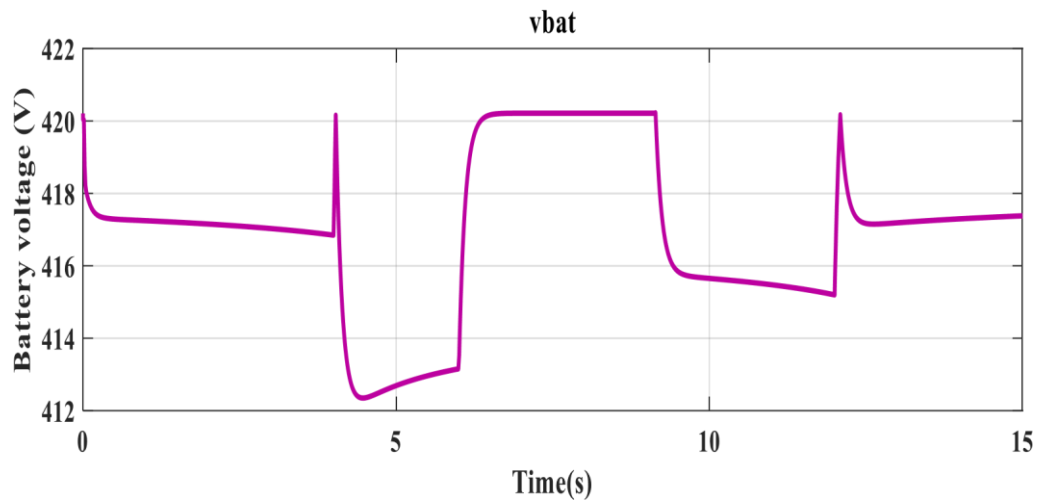
This diagram illustrates the change in DC bus voltage over time within a hybrid photovoltaic system. The voltage rises rapidly at startup, stabilizing at approximately 700 V, and then remains constant throughout the 0-15 second simulation period without any noticeable fluctuations or drops. This behavior reflects the effectiveness of the control system used to stabilize the voltage and maintain system stability. It also demonstrates the good performance of the electronic inverters in regulating and converting power within the system. Furthermore, the stability of the DC bus voltage indicates a continuous balance between the power generated by the solar panels and the power consumed or stored in the battery. This contributes to improved power regulation and efficient power flow management among the various system components. Therefore, the stability of the DC bus voltage can be considered an important indicator of the operational stability and safety of the hybrid photovoltaic system and the effectiveness of its control strategy.



**Figure III. 21:**DC bus voltage change

### III.5.8. Battery voltage curve:

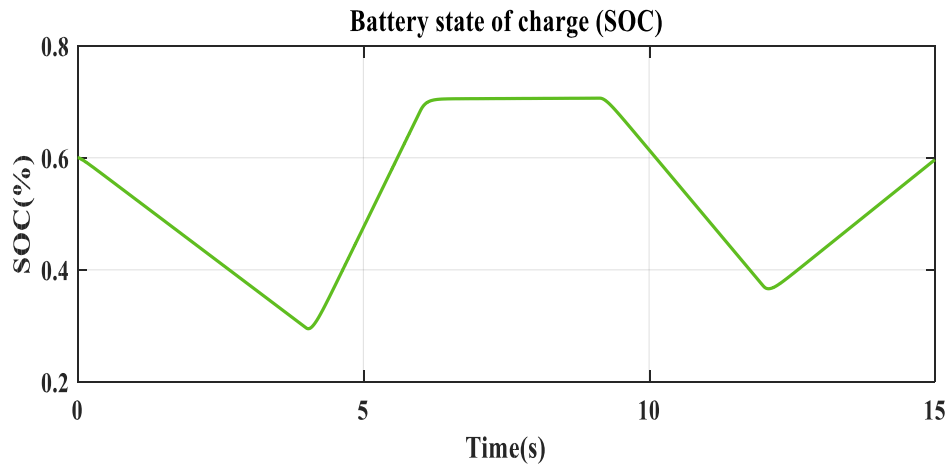
This diagram illustrates the change in battery voltage over time during charging and discharging within a hybrid photovoltaic system. The voltage fluctuates within a range of approximately 412 V to 420 V. The curve shows three main phases. In the first phase, from 0 to 4 seconds, the battery voltage gradually decreases, indicating that the battery is operating in a discharge state to supply power to the load. In the second phase, from 4 to 9 seconds, the voltage rises significantly to approximately 420 V. This is due to the increased power output from the solar panels and the battery entering a charging phase. Then, in the third phase, starting after 9 seconds, the voltage begins to decrease again as the load increases or the solar power decreases, causing the battery to return to a discharge state. The rapid rises and falls observed in the curve reflect the continuous change in the system's operating state and the battery's transition between charging and discharging modes, a normal behavior in smart hybrid systems. In general, this diagram shows that the battery responds dynamically to changes in operating conditions, which contributes to achieving energy balance and ensuring the stability of the electrical supply by storing excess energy and using it when needed.



**Figure III, 22:**Battery voltage change

### III.5.9. Battery State of Charge (SOC) Curve:

This diagram represents the change in the battery's State of Charge (SOC) over time. The SOC value is a percentage of the amount of energy stored in the battery. We observe that the SOC value fluctuates within a range of 0.3 to 0.7, indicating that the battery is operating within safe limits, maintaining its efficiency and lifespan. In the first phase, from 0 to 4 seconds, the SOC value drops from approximately 0.6 to 0.3, indicating that the battery was discharged to supply the load with electrical power. During the second phase, from 4 to 6 seconds, the SOC value rises rapidly to approximately 0.7 due to the increased power output from the solar panels and the commencement of battery charging. Subsequently, during the period from 6 to 9 seconds, the SOC value remains relatively stable, indicating a stable charging process or a balance between charging and discharging within the system. In the fourth stage, lasting from 9 to 12 seconds, the SOC value drops again due to increased energy demand or decreased solar irradiance. In the final stage, from 12 to 15 seconds, it begins to gradually rise again, reflecting the battery's return to charging mode. The SOC curve is considered one of the most important indicators in photovoltaic systems because it allows for monitoring the battery's condition and protecting it from overcharging or deep discharging, in addition to improving its operational lifespan and ensuring intelligent energy management. In general, this curve demonstrates that the battery plays a crucial role in supporting the stability of the hybrid photovoltaic system by continuously adapting to changes in solar output and electrical load to ensure a continuous power supply.



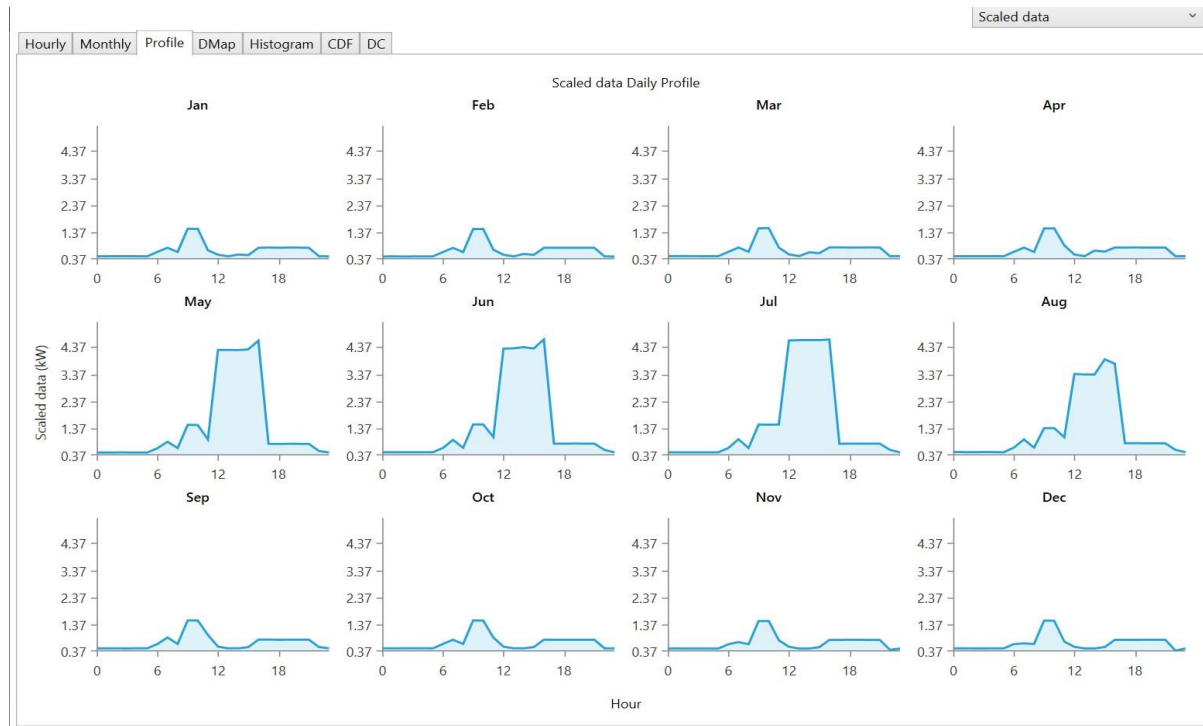
**Figure III, 23:**Battery state of charge - SOC

## **III.6. Explanation and analysis of a hybrid renewable energy system report using HOMER (Hybrid Optimization of Multiple Energy Resources) Pro**

### **III.6.1. HOMER(Hybrid Optimization of Multiple Energy Resources) Pro program:**

This report is based on HOMER (Hybrid Optimization of Multiple Energy Resources) Pro software, which specializes in designing and simulating hybrid renewable energy systems. It presents a case study of an electrical system based on photovoltaic (PV) solar panels and the electrical grid, with the option to add batteries and sell surplus energy back to the grid. This system aims to power a home or small facility while reducing conventional electricity consumption and improving reliance on clean energy.

The software analyzes the system's technical and economic performance by calculating energy



**Figure III. 24:**Daily electricity consumption and generation curves in kilowatts

production and consumption, examining operating and investment costs, and comparing several scenarios to select the optimal solution in terms of efficiency and cost. The simulation results demonstrate that integrating solar energy with the electrical grid contributes to improved electricity supply stability and reduced dependence on conventional energy sources, particularly given the high solar irradiance in Algeria.

### III.6.2. Electrical load curve (Load Profile):

The load profile and table above represent the evolution of energy consumption throughout the year, from January to December. This load shows relative stability across all months, with no significant changes in annual demand. The facility records its highest consumption during the daytime, specifically between 12:00 and 16:00, when the peak load reaches approximately 2.9 kW. This alignment between peak energy demand and peak solar irradiance is a positive factor, as it enhances the efficiency of solar energy utilization and reduces the need for battery storage.

### III.7. Detailing and comparing the three studied cases

#### III.7.1. Case 1: A grid-connected solar power system (PV + Grid) without selling energy:

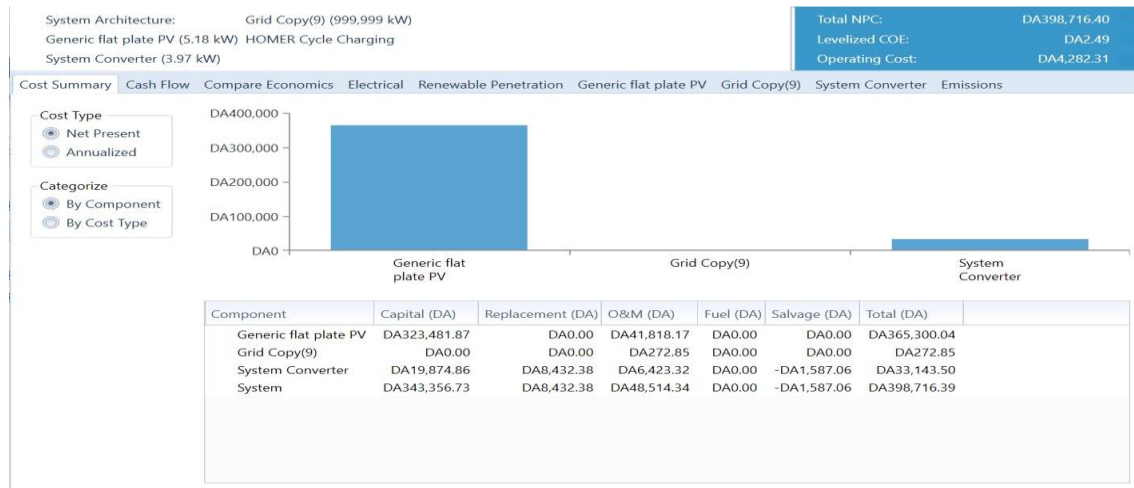
The first scenario represents a hybrid system that relies solely on integrating photovoltaic panels with the electrical grid, without any battery storage or mechanism for selling surplus energy. This system consists of a 5.18 kW solar array and a 3.97 kW inverter, both connected directly to the electrical grid, and operates on the principle of immediate self-consumption of the generated energy.



**Figure III. 25:**Results of electrical simulation and monthly electrical production (HOMER)

From an economic and technical standpoint, this system requires an initial investment to purchase and install the essential components, with the investment cost estimated at approximately 343,357 Algerian dinars. Despite this, the system demonstrates high economic viability, contributing to a reduction in the total current cost (NPC) to 398,716 Algerian dinars and lowering the cost of electricity production to approximately 2.49 Algerian dinars/kWh, reflecting a significant improvement in economic efficiency.

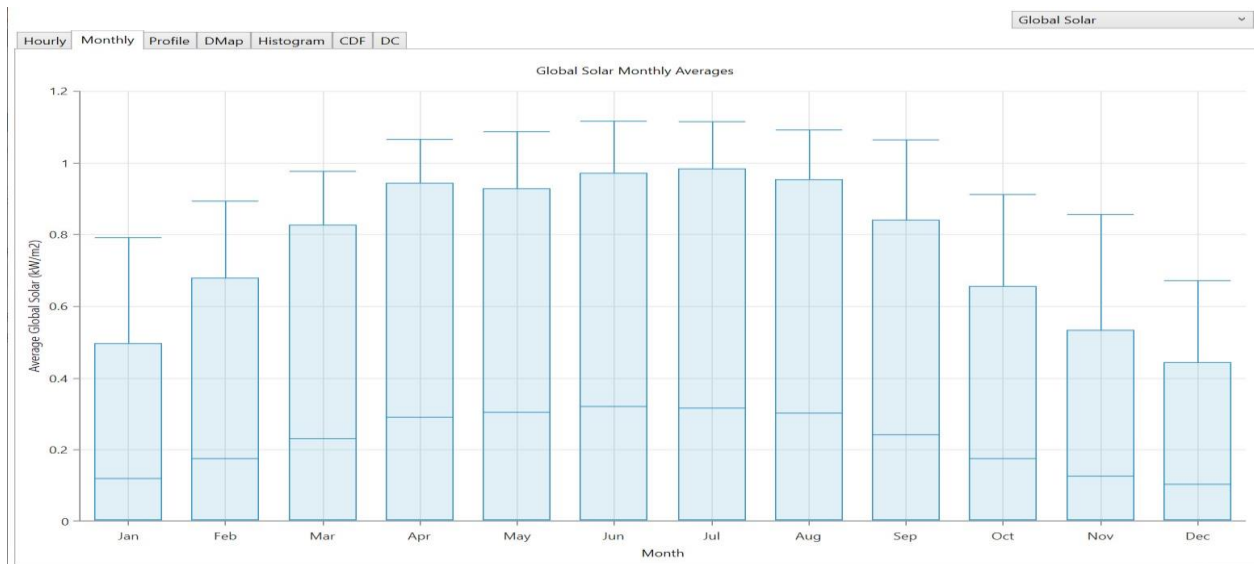
Financially, the project achieves a payback period of approximately 9 years, with an internal rate of return (IRR) of 10%, indicating stable and acceptable profitability for the medium-term investment.



**Figure III. 26:**Net Present Cost (NPC) breakdown by component in HOMER

In terms of energy flow, the system covers a significant portion of the demand through solar production during daylight hours, generating approximately 8,898 kWh annually, which covers roughly 68.9% of total consumption. The energy deficit at night is compensated for by the electrical grid, which supplies approximately 4,012 kWh annually, or 31.1%. This brings the total renewable energy coverage within the facility to approximately 67.6%.

Furthermore, this system is characterized by a significant decrease in unused excess energy, not exceeding 81.2 kWh annually (0.629%). This reflects the precision of the system design and the alignment of the panel capacity with the daytime electrical load, thus achieving nearoptimal utilization of solar energy production.



**Figure III. 27:**Global Solar Monthly Averages in HOMER

### III.7.2. Case 2: Solar system + batteries + grid:

This case represents a more advanced hybrid system, maintaining a connection to the electrical grid while adding EnerSys Power Safe SBS 1800 energy storage units. These units store surplus solar energy for use during periods of low production or at night. The system consists of a 5.19 kW solar panel array, two batteries, and a 3.45 kW inverter, allowing for improved energy utilization and reduced direct reliance on the electrical grid.

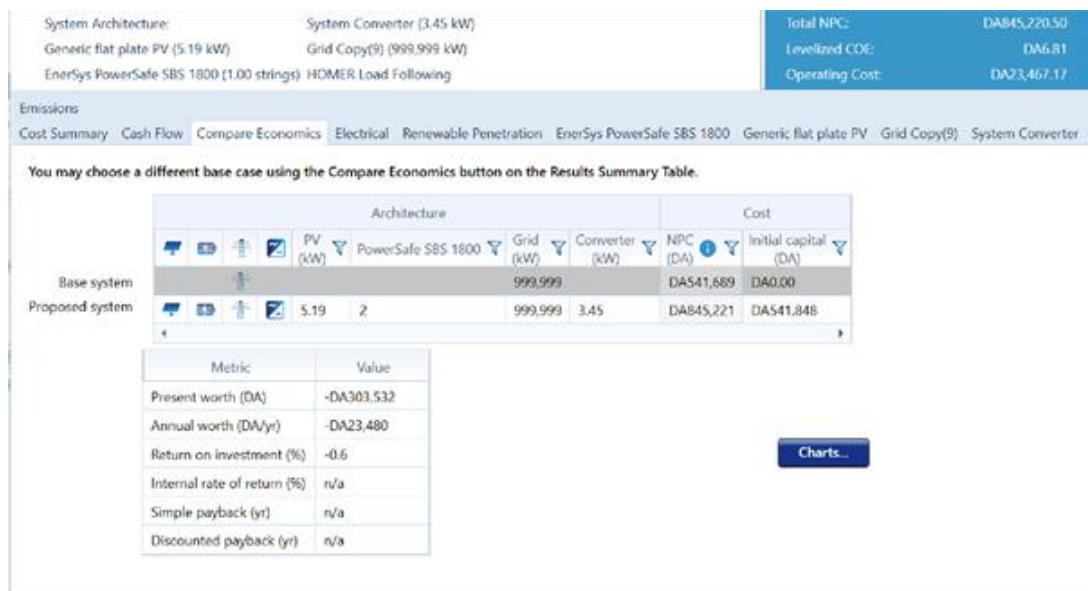


**Figure III. 28:**Cash flow breakdown by cost type over the project lifetime in HOMER

Economically, the addition of batteries significantly increased the initial investment cost, reaching approximately 541,848 Algerian dinars. This is primarily due to the high prices of batteries and storage equipment. This also negatively impacted the system's economic indicators, as the total present cost (NPC) rose to 845,221 Algerian dinars, while the cost of energy production (LCOE) reached 6.81 DZD/kWh, a value higher than the cost of conventional electricity purchased from the grid.

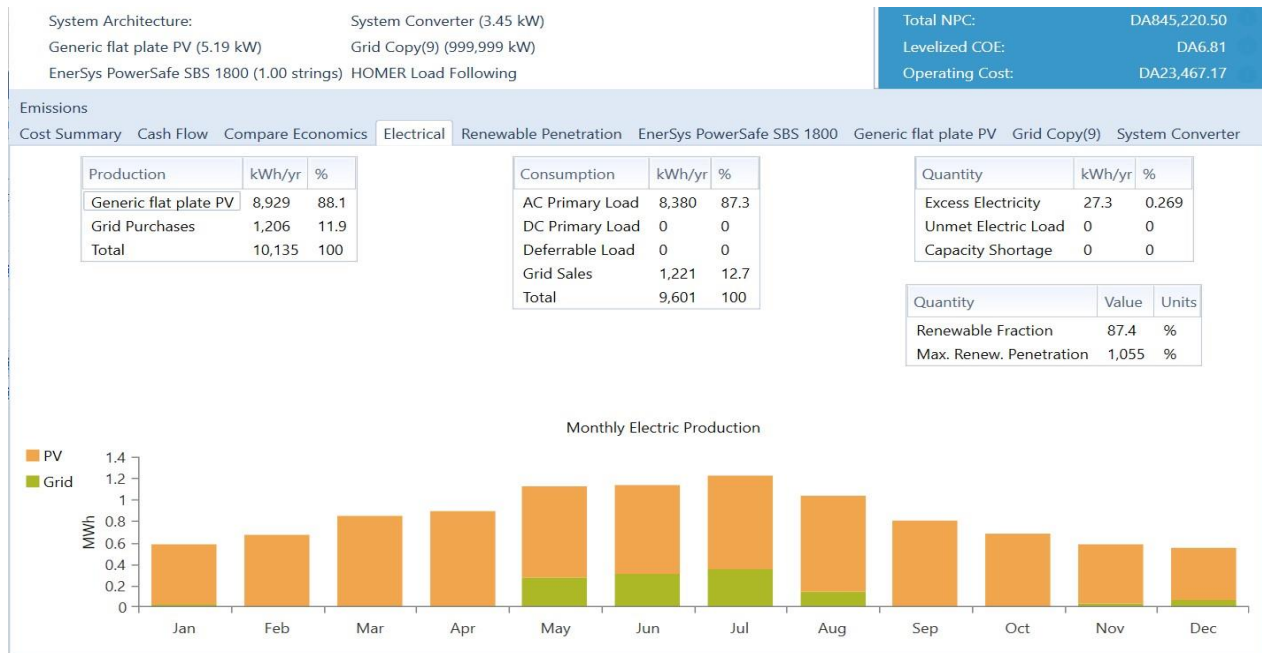
In terms of financial profitability, the system recorded a negative return on investment (ROI) of -0.6%, indicating the limited economic viability of this option under current conditions in Algeria, especially given the limited lifespan of the batteries and the high costs of their replacement and maintenance.

In terms of energy performance, the batteries significantly reduced reliance on the electricity grid, with the amount of energy purchased from the grid decreasing to approximately 1,206 kWh annually, equivalent to 11.9% of total electricity consumption. Conversely, the contribution of renewable energy sources within the facility increased to 87.4%, reflecting a significant improvement in the system's energy independence.



**Figure III. 29:**Economic comparison between the base system and the proposed system in HOMER.

Environmentally, the system achieved positive results by reducing carbon dioxide emissions to approximately 762 kg/yr, making it more environmentally friendly compared to a conventional system. However, the study concluded that while incorporating batteries contributed to increased system efficiency and a higher reliance on renewable energy, it also reduced the project's economic viability due to the high cost of batteries and their short operational lifespan.



**Figure III. 30:**Electrical simulation results and monthly electric production in HOMER.

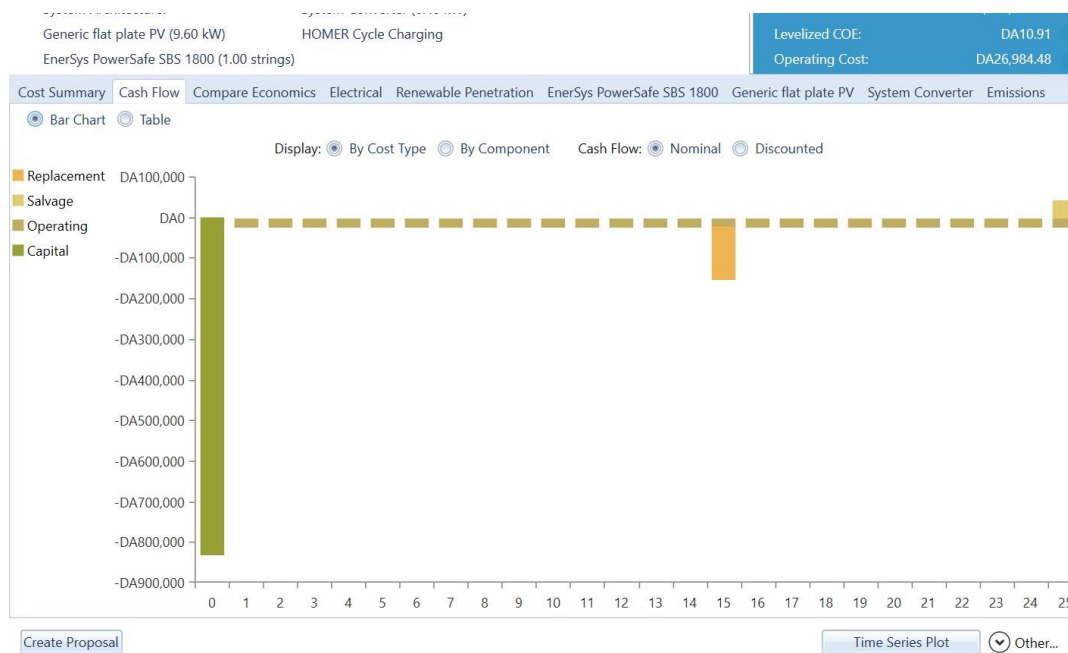
### III.7.3. Case 3: Off-Grid Solar Power System with Battery

This case represents a photovoltaic system completely isolated from the electrical grid, relying entirely on solar energy and batteries to meet the facility's electricity demand. This type of system is known as a stand-alone or off-grid system, as there is no possibility of tapping into the grid during periods of low production or high consumption.

To ensure continuous power supply at night and during periods of low solar irradiance, the solar field capacity was increased to 9.60 kW, with the use of a 6.40 kW inverter and a battery storage system. This significant expansion of system components was necessitated by the absence of the electrical grid, which served as a backup power source in the previous cases.

Economically, this system is the most expensive of all the cases studied, requiring a very high initial investment due to the increased number of panels, batteries, and associated equipment. The total present cost (NPC) also increased significantly, reaching 1,180,906

Algerian dinars, while the cost per kilowatt-hour (kWh) reached approximately 10.91 DZD/kWh, the highest value recorded in the study. This reflects the limited economic viability of this type of system under current conditions.



**Figure III. 31:** Cash flow breakdown by cost type over the project lifetime in HOMER

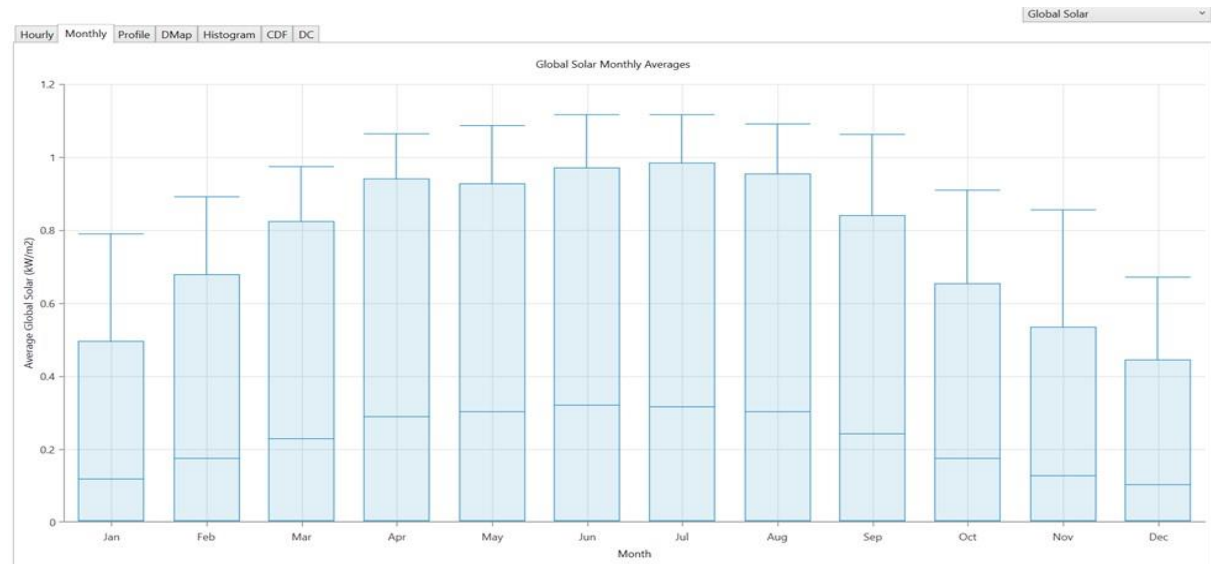
In terms of energy performance, the system achieved complete energy independence, with renewable energy covering 100% of the facility's electricity needs without any reliance on the grid. Annual solar energy production reached approximately 16,506 kWh/yr, a high figure compared to other cases.



**Figure III. 32:**Electrical simulation results and monthly electric production in

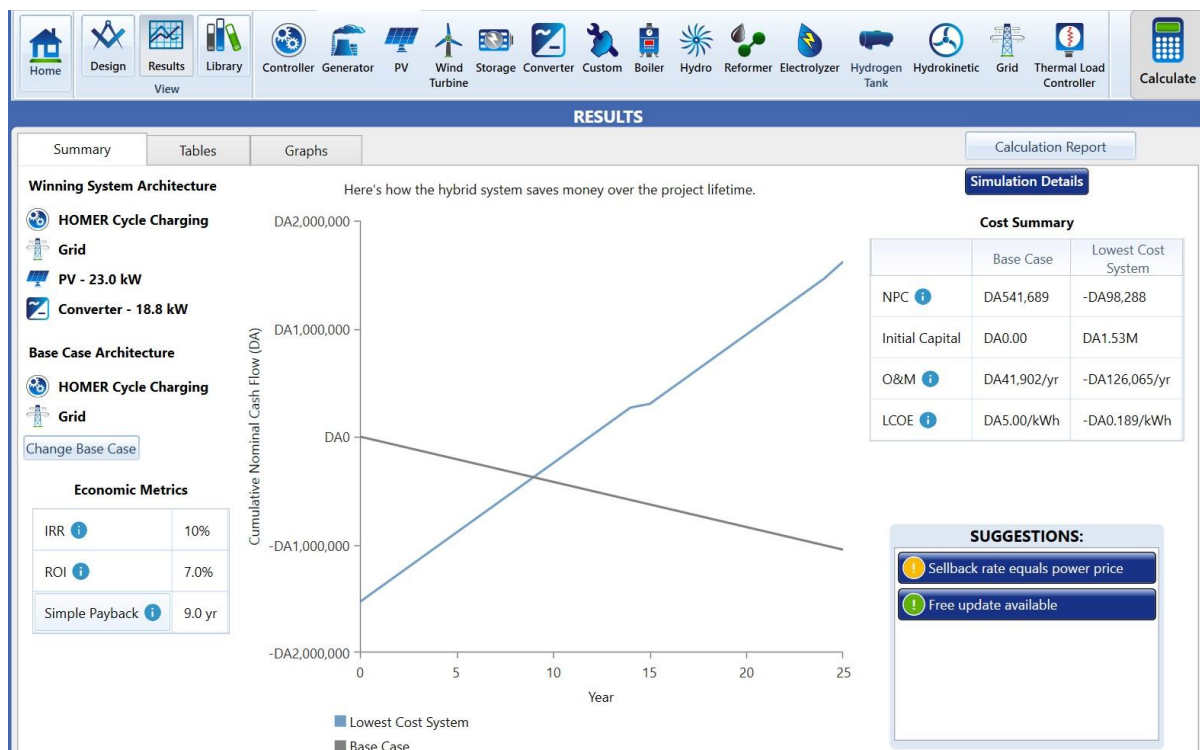
Despite this positive aspect of complete reliance on clean energy, the system exhibited a HOMER significant technical problem: a high amount of unutilized surplus energy. The electricity surplus reached approximately 7,601 kWh/yr, representing a loss of nearly 46% of the total annual production, a very high percentage. This is due to the large size of the solar field compared to the electrical load, in addition to the batteries becoming fully charged during daylight hours. This results in a significant loss of generated energy because there is no electrical grid to distribute the excess.

Therefore, from an engineering perspective, these results confirm that fully isolated systems require increased generation and storage capacity to ensure continuity. However, this leads to higher costs and significant losses of unused energy, thus reducing their economic efficiency despite achieving complete energy independence.



**Figure III. 33:**Global Solar Monthly Averages in HOMER

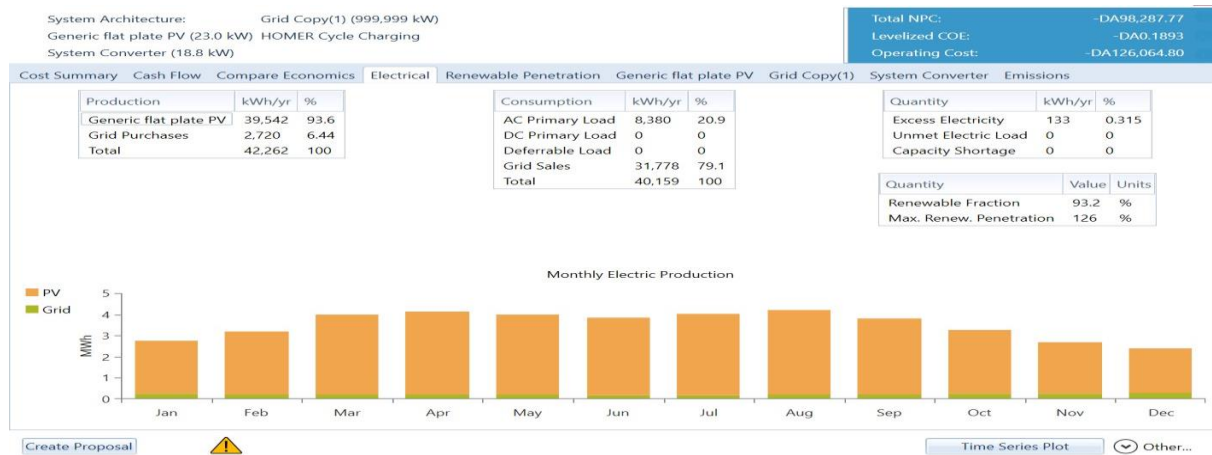
### III.7.4. Case 4: Grid-Connected Solar Power System with Excess Energy Sale (PV + Grid + Sellback):



**Figure III. 34:**Results summary and cumulative nominal cash flow comparison in HOMER.

This case represents the most advanced system from an investment perspective. It relies on grid connection with the activation of a feature that allows for the sale of surplus energy. In this

model, the solar field has been significantly amplified to a capacity of 23.0 kW, utilizing an 18.8 kW inverter. This not only covers the facility's electrical needs but also transforms it into a power generation unit capable of supplying electricity and selling it to the public grid.



**Figure III. 35:**Electrical simulation results and monthly electric production in HOMER.

Technically, the system utilizes solar energy during daylight hours to initially power local loads. The surplus is then fed directly into the electrical grid to generate additional revenue. This approach reflects the concept of investing in renewable energy rather than solely relying on self-consumption.

Economically, this system is the best among all the cases studied, despite the high initial investment cost, which reached approximately 1,531,416 Algerian dinars, due to the significant increase in the number of panels and the inverter capacity. However, the simulation results showed that this investment yields very high returns in the long term.

The total present cost (NPC) registered a negative value of approximately -98,287.77 DA, and the cost of energy production (LCOE) also became negative at -0.1893 DA/kWh. In the HOMER program, these negative values indicate that the project not only covered its operating and investment costs but also began generating net profits by selling electricity to the

grid, making this system the most profitable and economically viable among all the scenarios studied.

In terms of energy balance, the annual solar energy production reached approximately 39,542 kWh/yr, the highest production value recorded in the study. After meeting the facility's needs, approximately 31,778 kWh/yr was sold to the electricity grid,

representing 79.1% of the total energy produced. This confirms that the system functions as an energy production and investment plant rather than simply a consumption system.

Conversely, the amount of energy purchased from the grid decreased to a very small percentage, estimated at only 6.44% of total consumption, while the contribution of renewable energy sources increased to approximately 93.2%, reflecting high efficiency from both an energy and environmental perspective.

Therefore, this system can be considered the optimal solution from a techno-economic standpoint, especially if a legal framework is in place that allows for the sale of electricity generated to the grid at incentivized prices. This approach combines reduced bills, financial gains, and increased reliance on renewable energy sources.

#### **VII.5. Case5 : Solar + Battery + Grid + Sellback System:**

This system represents the most integrated and complex, combining solar panels, batteries, and a connection to the electrical grid, with the ability to sell surplus energy. This type of system aims to achieve the highest degree of energy independence while benefiting economically from selling excess electricity to the public grid.



**Figure III. 36: Net Present Cost (NPC) summary by component in HOMER**

From an engineering perspective, the solar panels power the electrical loads during the day, while the surplus is stored in the batteries for later use at night or when solar irradiance is low. When the batteries are full and there is additional production, the surplus energy is fed directly into the electrical grid for sale, generating revenue. The grid can also support the system during periods of high demand or low renewable energy production.

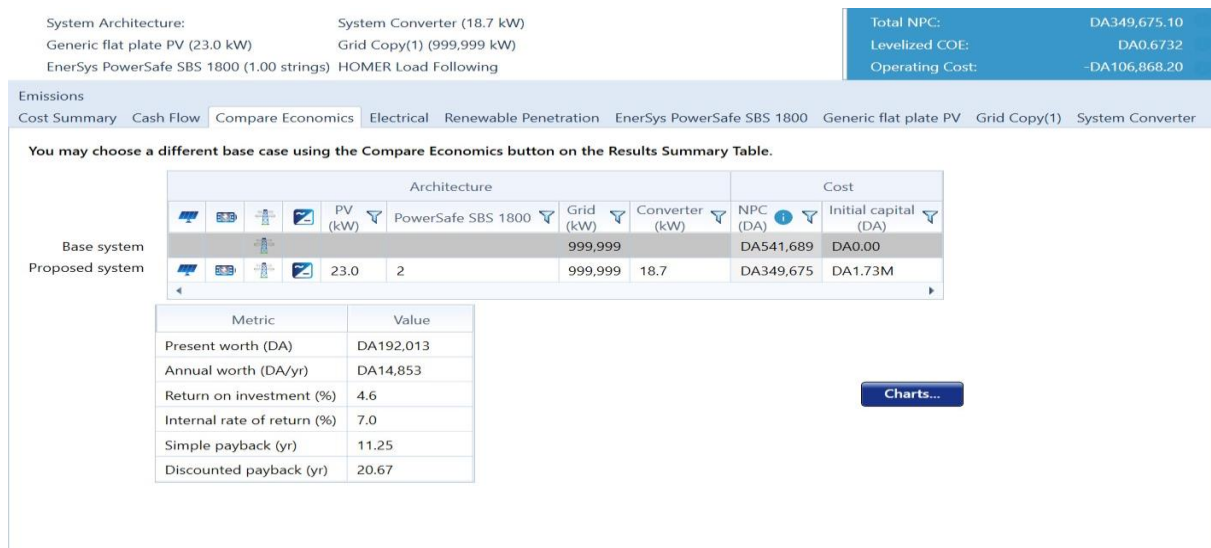
Technically, this system is characterized by high operational flexibility, as it ensures a continuous power supply even in cases of grid outages or low solar output, thanks to the batteries serving as a backup power source. It also allows for improved utilization of solar energy and reduced loss of surplus compared to isolated systems.



**Figure III. 37:**Electrical simulation results and monthly electric production in HOMER.

Economically, the system offers the potential for a significant reduction in electricity bills, along with additional profits from selling energy back to the grid. However, economic viability depends directly on the cost of the batteries, the selling price of electricity, and the lifespan of the storage system. In some cases, batteries may lead to higher initial investment and recurring costs, thus extending the payback period compared to a grid-connected system without batteries.

From an environmental perspective, this system achieves a very high degree of reliance on renewable energy, while reducing conventional energy consumption and lowering carbon dioxide emissions, making it one of the most sustainable and suitable solutions for the modern energy transition.



**Figure III. 38:** Economic comparison and metrics between the base system and the proposed system in HOMER.

### III.8. Conclusion:

This Chapter addressed the practical aspects and analyzed the simulation results for the hybrid photovoltaic system using the HOMER Pro software. Several configurations were compared to select the optimal system from a technical and economic perspective.

The results showed that integrating solar panels with batteries and the electrical grid contributes to improving the stability of the energy supply and reducing dependence on the traditional grid, as well as lowering operating costs and polluting emissions. The study also showed that the proposed system achieved good economic returns through a lower net total cost (NPC) and improved investment indicators such as internal rate of return (IRR) and payback period.

The results further confirmed the effectiveness of grid-connected hybrid systems in optimizing solar energy utilization and ensuring a continuous electricity supply, making them a promising solution for meeting the growing demand for energy in a sustainable and environmentally friendly manner.

# ***General Conclusion***

## **General Conclusion**

This study confirms that hybrid grid-connected photovoltaic systems are effective solutions for addressing current energy and environmental challenges. By integrating solar panels, batteries, and the electrical grid, these systems ensure continuous power supply, improve energy efficiency, and reduce dependence on fossil fuels.

The results showed that Algeria has strong potential for solar energy development due to its large desert areas and high solar irradiance. This makes solar energy an important strategic option for supporting the energy transition and conserving traditional energy resources.

The study also highlighted the important role of system components such as batteries, inverters, and control systems, whose performance is influenced by climatic conditions and energy demand. Storage systems help improve supply stability and reduce grid dependence during low solar production periods.

Simulation tools like MATLAB/Simulink and HOMER Pro demonstrated that gridconnected systems provide the best balance between technical and economic performance, while battery-based systems offer greater energy independence despite higher costs.

In addition, smart technologies such as EMS, IoT, and smart meters improve monitoring, energy management, and system efficiency. Economically and environmentally, systems capable of selling surplus electricity to the grid provide long-term financial benefits and reduce carbon emissions.

Overall, hybrid photovoltaic systems supported by intelligent control technologies represent a promising future solution for achieving sustainable development, energy security, and clean energy transition.

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# Abstract

## Abstract:

This study aimed to analyze the performance of hybrid photovoltaic systems using MATLAB, software. The results showed that the grid-connected system was the most economically efficient, with an investment cost of approximately 343,000 DZD and a payback period of nearly 9 years. The system selling surplus energy also achieved the best profitability by generating revenue and reducing energy costs. Battery-based or off-grid systems offered greater energy independence but were more expensive. Overall, the study confirmed that solar energy represents an effective and economical solution for reducing conventional energy consumption in Algeria.

**Keywords:** Solar energy - Photovoltaic system - Hybrid system - MATLAB - Renewable energy.

## Résumé :

Cette étude visait à analyser les performances de systèmes photovoltaïques hybrides à l'aide du logiciel MATLAB. Les résultats ont montré que le système raccordé au réseau était le plus rentable, avec un coût d'investissement d'environ 343 000 DZD et un retour sur investissement en près de 9 ans. Le système de vente du surplus d'énergie a également atteint la meilleure rentabilité en générant des revenus et en réduisant les coûts énergétiques. Les systèmes à batteries ou hors réseau offraient une plus grande indépendance énergétique, mais étaient plus coûteux. Globalement, l'étude a confirmé que l'énergie solaire représente une solution efficace et économique pour réduire la consommation d'énergie conventionnelle en Algérie.

**Mots-clés :** Énergie solaire - Système photovoltaïque - Système hybride - MATLAB- Énergie renouvelable

**الملخص:** تهدف هذه الدراسة إلى تحليل أداء الأنظمة الكهروضوئية الهجينة باستخدام برنامج الماتلاب. أظهرت النتائج أن النظام المرتبط بالشبكة الكهربائية هو الأكثر كفاءة اقتصادياً، حيث بلغت تكلفة الاستثمار حوالي 343 ألف دج مع فترة استرجاع تقارب 9 سنوات. كما حقق نظام بيع فائض الطاقة أفضل مردودية من خلال تحقيق أرباح وتقليل تكلفة الطاقة. أما الأنظمة المعتمدة على البطاريات أو المعزولة عن الشبكة فقد وفرت استقلالية طاقة أكبر ،

لكنها كانت مرتفعة التكلفة. وبشكل عام، أكدت الدراسة أن الطاقة الشمسية تمثل حلاً فعالاً واقتصادياً لتقليل استهلاك الطاقة التقليدية في الجزائر.

الكلمات المفتاحية: الطاقة الشمسية - النظام الكهروضوئي - النظام الهجين - الماتلاب - الطاقة المتجددة