Université Mohamed Khider de Biskra
Faculté des Sciences et de la Technologie
Département de génie électrique

MÉMOIRE DE MASTER

Sciences et Technologies
Electrotechnique
Énergie renouvelable

Réf. : ………………………………….

Présenté et soutenu par :
Morsli Abdelkader Hassani Mohamed Imad eddine

Le : lundi 2 juin 2025

Design, Performance Analysis, and Economic Feasibility of a Grid-Connected PV System

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Année universitaire : **2024 - 2025**

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Hassani Mohamed Imad eddine

Avis favorable de l'encadreur : Bekhoucha Nassima

Signature Avis favorable du Président du Jury

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Abstract

This thesis presents a study and implementation of a grid-connected photovoltaic (PV) system integrated without an energy storage solution. The objective is to optimize solar energy utilization in a typical residential setting located in Ain Sefra, Algeria, a region characterized by high solar irradiance. The work involves a comprehensive sizing process based on real household energy needs, solar resource assessment, and system configuration including PV modules, inverters, and battery storage. Simulation tools are used to evaluate the system's performance, efficiency, and economic viability. The study concludes with recommendations for enhancing the reliability and sustainability of solar energy deployment in similar regions.

الملخص :

تركز هذه المذكرة على دراسة وتحقيق نظام كهروضوئي مرتبط بالشبكة الكهربائية دون نظام تخزين. يهدف هذا العمل إلى تصميم حل موثوق وفعال للطاقة الشمسية موجه لمنزل سكني نموذجي في مدينة عين الصفراء بالجزائر، التي تتميز بمعدل إشعاع شمسي مرتفع. تشمل الدراسة تحليلًا مفصلًا للحمل الكهربائي، وحساب الأبعاد المثلى للنظام، واختيار المكونات، بالإضافة إلى محاكاة الأداء باستخدام أدوات مهنية متخصصة. كما تم إجراء تقييمات تقنية واقتصادية لتحديد مدى جدوى المشروع وفاعليته من حيث التكلفة. وتُظهر النتائج إمكانية الاعتماد على الأنظمة الكهروضوئية المرتبطة بالشبكة في تقليل فواتير الكهرباء ودعم التحول الطاقوي في الجزائر.

Résumé :

Ce mémoire porte sur l'étude et la réalisation d'un système photovoltaïque (PV) connecté au réseau sans stockage d'énergie. L'objectif est de concevoir une solution solaire fiable et performante adaptée à une maison résidentielle typique située à Aïn Séfra, en Algérie, une région bénéficiant d'un fort ensoleillement. L'étude comprend une analyse détaillée de la consommation énergétique, le dimensionnement du système, le choix des composants, ainsi qu'une simulation de performance à l'aide d'outils professionnels. Des évaluations techniques et économiques sont également menées pour juger de la faisabilité et de la rentabilité du système. Les résultats démontrent le potentiel des systèmes PV raccordés au réseau pour réduire les factures d'électricité et contribuer à la transition énergétique en Algérie.
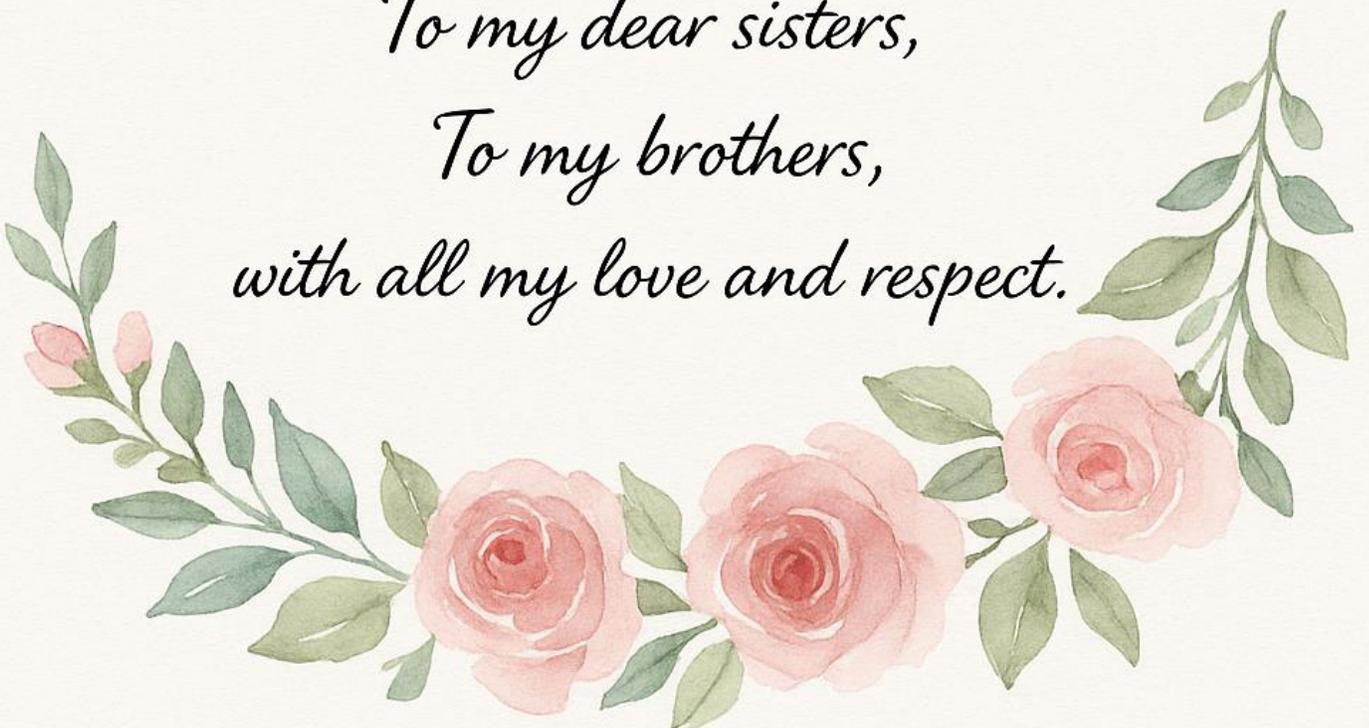
Dedication

I dedicate this modest work to
the most cherished people in heart:
my beloved mother and father, whose
unwavering support throughout my stu-
dies will forever be remembered with
deep gratitude.

To my dear sisters,
To my brothers,
with all my love and respect.

Thanks

First and foremost, I extend my deepest gratitude to God, the Creator, who granted me the strength, determination, and perseverance necessary to bring this work to completion.

I am sincerely thankful to my thesis supervisor, **Dr.Bekhoucha Nassima**, for her constant encouragement, dedication, and expert guidance. Her support and the generous time she devoted throughout the academic year were instrumental in shaping the outcome of this research.

I would also like to express my appreciation to **Dr. Boumaaraf Rabia**, Chair of the Jury, and to **Dr.Kiyyour Brahim**, for their interest in this work, their valuable time, and their contribution to the thesis evaluation and discussion.

Finally, I warmly thank all those who, in one way or another, contributed to the realization of this work.

List of figures

I **:** Courant de sortie / Output current (A)

V **:** Tension de sortie / Output voltage (V)

I_{SC} **:** Courant de court-circuit / Short-circuit current (A)

I_0 **:** Courant de saturation inverse / Reverse saturation current (A)

q **:** Charge élémentaire d'un électron ($\approx 1,602 \times 10^{-19}$ C)

k **:** Constante de Boltzmann ($\approx 1,38 \times 10^{-23}$ J/K)

T **:** Température absolue / Absolute temperature (K)

R_s **:** Résistance série / Series resistance (Ω)

R_p **:** Résistance parallèle (shunt) / Shunt resistance (Ω)

FF **:** Facteur de forme / Fill factor (sans unité)

η **:** Rendement de la cellule PV / Efficiency of a PV cell (%)

G **:** Irradiance solaire / Solar irradiance (W/m² or kWh/m²/day)

P_{max} **:** Puissance maximale / Maximum power output (W)

V_{oc} **:** Tension en circuit ouvert / Open-circuit voltage (V)

I_{mp} **:** Courant au point de puissance max / Current at MPP (A)

V_{mp} **:** Tension au point de puissance max / Voltage at MPP (V)

PR **:** Taux de performance / Performance ratio (dimensionless)

E_d **:** Consommation énergétique quotidienne / Daily energy demand (kWh/day)

E_{ann} **:** Consommation énergétique annuelle / Annual energy demand (kWh/year)

P_{PV} **:** Puissance PV installée requise / Required PV capacity (kWp)

N **:** Nombre de modules PV / Number of PV modules

A **:** Surface de l'installation PV / Area of array (m²)

S **:** Section du câble / Cable cross-sectional area (mm²)

L **:** Longueur du câble / Cable length (m)

ΔV **:** Chute de tension / Voltage drop (V)

γ **:** Conductivité du cuivre / Copper conductivity (~56 m/$\Omega \cdot$mm²)

I_{AC} **:** Courant alternatif en sortie d'onduleur / Inverter AC current (A)

V_{AC} **:** Tension en courant alternatif / AC voltage (V)

η_{inv} **:** Rendement de l'onduleur / Inverter efficiency (%)

HS **:** Hauteur solaire / Solar elevation angle (°)

AZ **:** Azimut solaire / Solar azimuth angle (°)

θ **:** Angle d'inclinaison des panneaux / Tilt angle (°)

ϕ **:** Latitude du site / Site latitude (°)

C_{inv} **:** Coût de l'onduleur ou son remplacement / Inverter cost (DZD)

ROI **:** Retour sur investissement / Return on investment (%)

CO_2 **:** Émissions de dioxyde de carbone / CO₂ emissions (kg or tons)

θ_{opt} **:** Angle d'inclinaison optimal / Optimal tilt angle (°)

E_{PV} **:** Énergie produite par le système PV / Energy produced (kWh/year)

C_{init} **:** Coût initial de l'investissement / Initial investment (DZD)

C_{tot} **:** Coût total sur le cycle de vie / Total cost (DZD)

S_{year} : Économies annuelles / Yearly savings (DZD/year)

t_{pb} : Durée d'amortissement / Payback period (years)

EF_{CO2} : Facteur d'émission CO_2 / CO_2 emission factor (kg/kWh)

E_{saved} : Énergie évitée du réseau / Energy offset from grid (kWh)

CO_2 : Émissions évitées annuellement / CO_2 saved annually (tons/year)

Y_f : Rendement final / Final yield (kWh/kWp/year)

Y_r : Rendement de référence / Reference yield (kWh/kWp/year)

$LCOE$: Coût actualisé de l'énergie / Levelized Cost of Energy (DZD/kWh or USD/kWh)

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General introduction

The global energy landscape is undergoing a significant transformation, driven by the urgent need to ensure long-term energy security and address the pressing threat of climate change. With electricity demand expected to grow by nearly 60% between 2023 and 2050 particularly in developing regions the pressure to shift toward cleaner sources of energy has never been greater. Traditional fossil fuels, although historically reliable, have contributed heavily to greenhouse gas emissions. Therefore, meeting international climate targets, such as those set by the Paris Agreement, requires a rapid and strategic transition to low-carbon energy systems.

Renewable energy sources offer a promising path forward. In particular, solar photovoltaic (PV) systems have emerged as a leading solution due to their minimal operational emissions and rapidly declining costs. Over the last decade, the levelized cost of electricity (LCOE) for solar PV has decreased by approximately 85%, making it one of the most competitive generation technologies globally. This cost reduction has been supported by advances in manufacturing, improvements in efficiency, and growing deployment experience. Furthermore, government policies such as feed-in tariffs, renewable energy mandates, and competitive procurement mechanisms have played a key role in accelerating investment and enabling economies of scale.

Beyond environmental and economic considerations, there are also important geopolitical motivations for renewable energy adoption. Countries that rely heavily on imported fossil fuels are vulnerable to supply disruptions and market volatility. Investing in domestic renewable energy capacity, especially solar PV, can reduce import dependency, enhance national energy sovereignty, and stimulate local job creation across manufacturing, installation, and maintenance sectors.

Solar PV holds a particularly strategic position within the broader spectrum of renewable technologies. Unlike large centralized power stations, PV systems are modular and scalable, allowing them to be installed close to the point of consumption. Rooftop systems, carports, and small ground-mounted arrays help reduce transmission losses and ease pressure on local distribution networks. In high-irradiance regions, PV can meet a significant portion of daytime electricity demand, which helps flatten peak loads and defer the need for costly grid infrastructure upgrades.

Coupling PV systems with energy storage solutions amplifies these benefits. Batteries enable time-shifting of electricity use, improve frequency regulation, and enhance the flexibility of power systems. This is particularly important as energy systems evolve to accommodate higher shares of variable renewables. Moreover, PV technology integrates well with emerging smart grid infrastructures. Modern PV inverters can deliver grid services such as voltage support and reactive power compensation, which contribute to better power quality and system reliability. As the adoption of electric vehicles and demand-side management technologies continues to grow, PV systems will play a central role in reducing dependence on centralized grids and increasing household and community-level energy autonomy.

Within this context, the present study aims to evaluate the technical design, performance, and economic feasibility of a grid-connected solar PV system tailored to a specific project site. The first objective is to determine the optimal system configuration by selecting appropriate PV modules and inverter capacities, as well as identifying the best tilt and orientation angles, based on solar resource availability and site-specific constraints.

Next, the study will assess the expected energy output using simulation tools combined with historical meteorological data. This analysis includes evaluating the capacity factor, performance ratio, and various system losses related to temperature, soiling, and component mismatch.

From an economic standpoint, the project's viability will be analyzed through financial indicators such as net present value (NPV), internal rate of return (IRR), levelized cost of energy (LCOE), and payback period. Sensitivity analyses will also be conducted to determine the impact of changes in key assumptions, such as electricity price trends and discount rates, on overall project performance.

Finally, the study will estimate the environmental benefits, particularly the reduction in carbon emissions resulting from decreased reliance on grid electricity. It will also consider the influence of local energy policies, incentive programs, and tariff structures on the economic attractiveness of the system

Chapitre I : Introduction And Background

I.1. Introduction

In recent years, the world has witnessed a growing demand for energy, driven by population growth, industrial development, and higher living standards. At the same time, concerns about environmental pollution and the depletion of fossil fuels have encouraged the search for clean and renewable energy sources. Solar energy, in particular, has become a leading alternative [1] due to its abundance and sustainability.

Photovoltaic (PV) systems, which allow the direct conversion of sunlight into electricity, have gained significant attention as a practical and efficient way to harness solar energy. Thanks to technological advancements, PV systems are now more reliable and cost-effective, leading to their widespread adoption in various sectors. This chapter aims to introduce the basic concepts of photovoltaic systems, covering their historical development, principles of operation, and the different types available. It also emphasizes the importance of PV systems in supporting the global transition towards renewable energy and building a more sustainable future.

I.2. Global Energy Trends and the Role of Solar PV

The global energy sector is rapidly changing due to rising energy demand, climate concerns, and the need for sustainable alternatives to fossil fuels. Solar photovoltaic (PV) systems have become a crucial solution because of their scalability, lower costs, and environmental advantages. Increasing electricity use drives the need for decentralized solar power. Efforts to reduce carbon emissions, such as the Paris Agreement [2], promote solar PV for its zero emissions. Additionally, the cost of solar electricity has fallen dramatically, making it one of the most affordable energy sources. Solar PV also enhances energy security by reducing reliance on imported fossil fuels.

I.3. Site Assessment and Solar Resource in Algeria

Algeria, with over 80% of its territory covered by desert, possesses exceptional solar energy potential due to its arid climate and high solar irradiation levels ranging from 1,700 to 2,650 kWh/m²/year. The southern regions, particularly, receive over 5.5 kWh/m²/day, making them ideal

for large-scale photovoltaic (PV) deployment. Despite challenges like dust accumulation and temperature fluctuations, these are manageable through proper maintenance. Ain Sefra, located in western Algeria, stands out for its stable semi-arid climate, minimal dust impact, and high solar irradiation, making it especially well-suited for solar projects. This aligns with Algeria's national renewable energy strategy (PNEREE) [3], which targets 15,000 MW of renewable capacity by 2035—much of it from solar. Maps will be used to further highlight high-potential solar regions across the country.
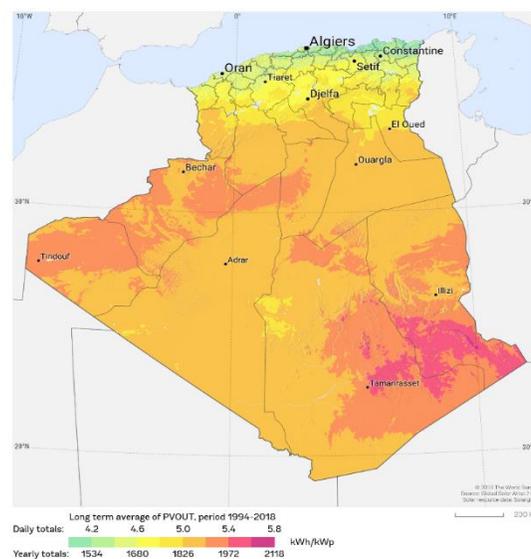
Figure (II.1): photovoltaic power potential in Algeria [9]

I.4. Geographic and climatic scope

I.4.1. Geographic and Climatic Considerations

Algeria's varied geography, from coastal areas to the Sahara Desert, influences its solar potential. Northern regions receive moderate sunlight, while southern deserts get high solar radiation above 5.5 kWh/m²/day, ideal for solar energy despite heat-related efficiency losses. For example, the 60 MW Laghouat solar plant, located near the Sahara, benefits from strong, stable sunlight, ensuring efficient power generation and helping reduce Algeria's dependence on fossil fuels.

Figure (I.2): 60 MW photovoltaic power plant, Laghouat, Algeria

I.4.1.1. Solar Irradiance

Solar irradiance is the sunlight power received per unit area on Earth's surface, usually measured in watts per square meter (W/m²). It directly affects the energy production of photovoltaic systems. Solar irradiance varies with location, time, weather, and atmospheric conditions. It includes direct sunlight (DNI), scattered sunlight (DHI), and reflected light, which together form the total solar energy available (GHI). Accurate measurement of solar irradiance is crucial for designing efficient and reliable solar energy systems

Irradiance Type	Value (kWh/m²/day)
Global Horizontal Irradiance (GHI)	5.1
Direct Normal Irradiance (DNI)	6.0
Diffuse Horizontal Irradiance (DHI)	1.1

Table (I.1): Solar Irradiance Data for Algeria
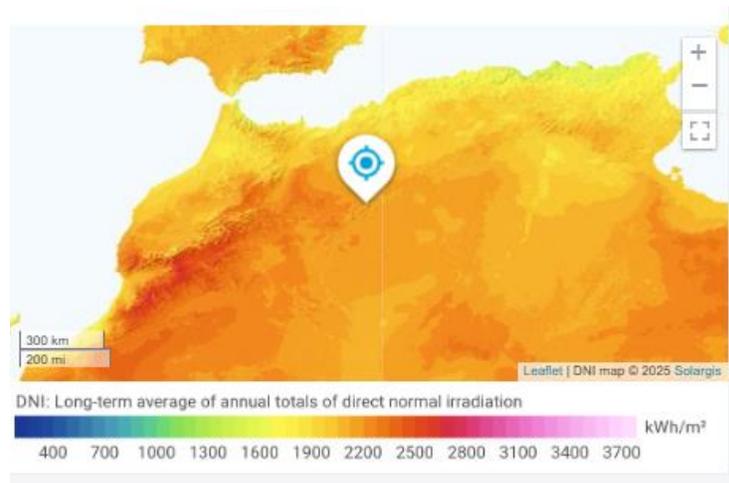
Figure (I.3) DNI Map in Algeria
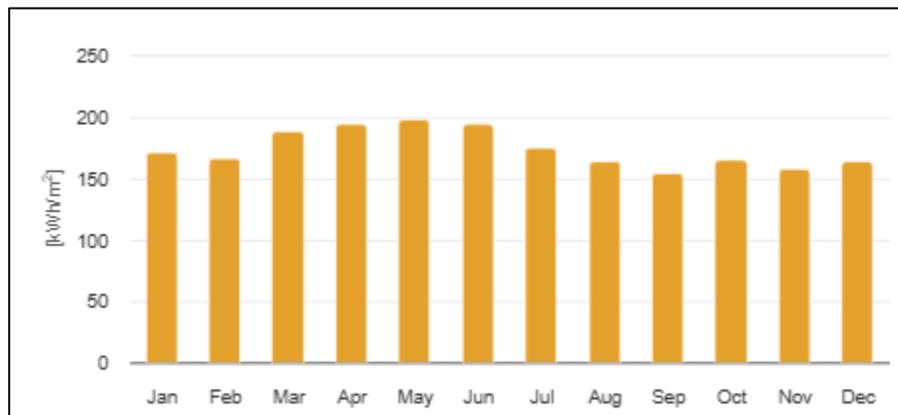
Figure (I.4) Monthly averages Direct normal irradiation

I.4.1.2. Temperature & Weather

Algeria has excellent solar potential, with high sunlight levels ranging from 4.5 to 6.5 kWh/m²/day and up to 3,900 sunshine hours annually. While high temperatures and dust can affect PV efficiency, regular maintenance helps maintain performance. Overall, Algeria's climate strongly supports solar energy development.
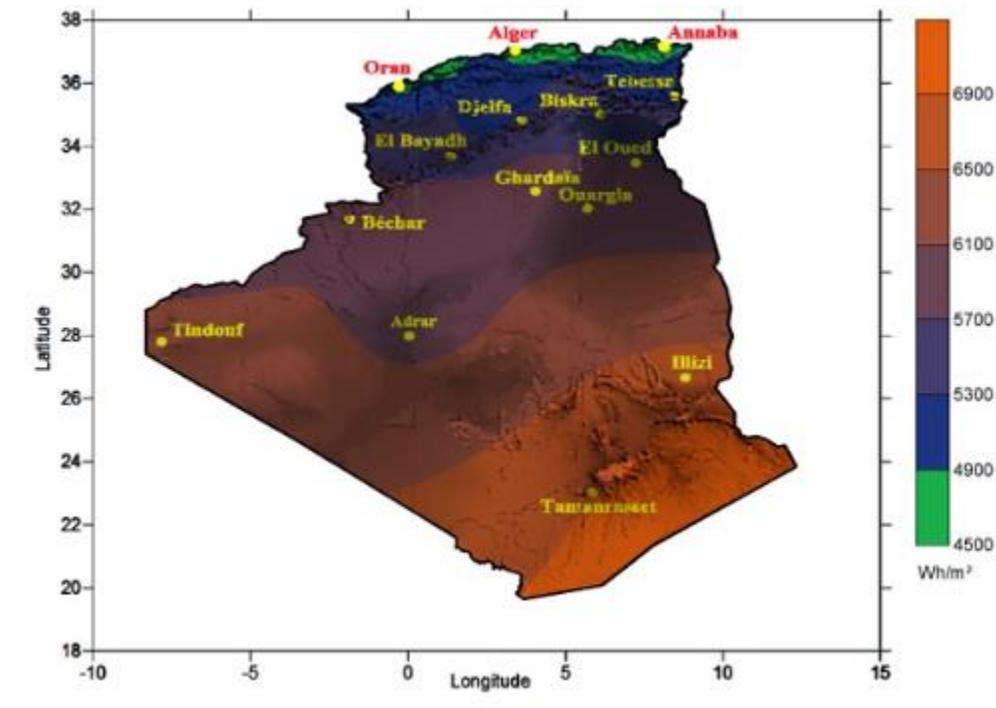
Figure(I.5): Annual Solar Irradiance Map of Algeria

I.4.2. Wind and Humidity Considerations

➢ Algeria's moderate wind conditions, especially in inland and southern regions, contribute positively to photovoltaic (PV) system performance by providing natural cooling, which helps reduce panel overheating and improve efficiency. However, these winds often carry dust and sand, particularly in arid zones, leading to accumulation on panel surfaces. This dust reduces the amount of sunlight reaching the PV cells, resulting in lower energy output. To ensure consistent performance, regular cleaning and maintenance of solar panels are necessary, especially in regions prone to frequent dust exposure.
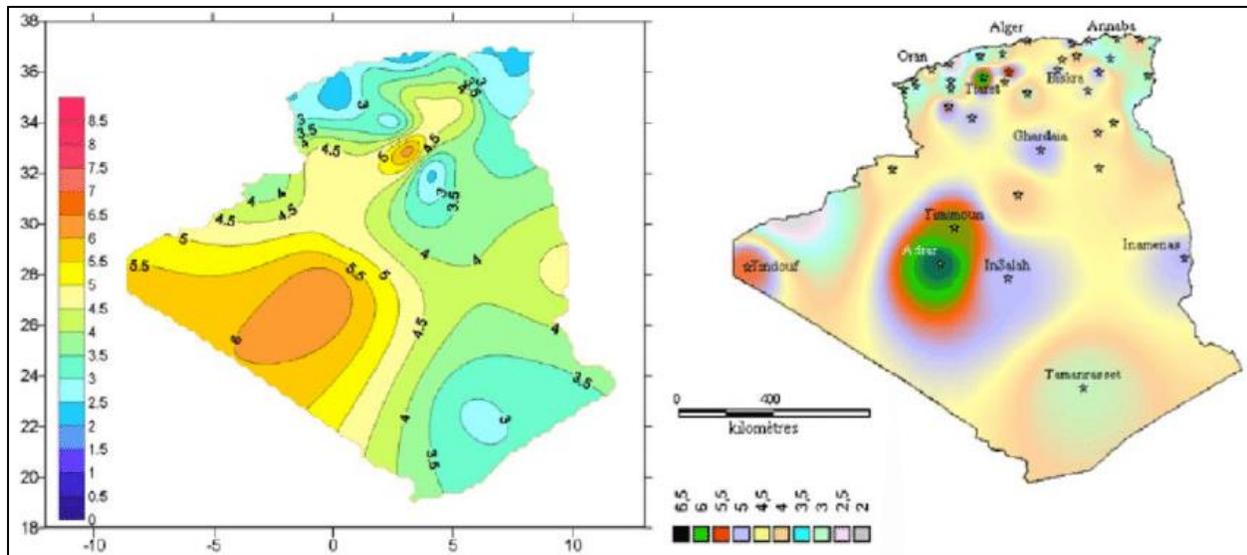
Figure (I.6): Annual maps of wind speed in Algeria at 10 m high 18

➢ Algeria generally experiences low to moderate humidity, especially in its inland and southern regions, creating favorable conditions for photovoltaic (PV) systems. Low humidity helps prevent moisture-related issues such as corrosion, oxidation, and internal damage to solar panels and electrical components. These dry conditions support the long-term durability and reliability of PV installations by reducing the risk of water vapor infiltration and maintaining system efficiency over time. Overall, Algeria's climate is well-suited for sustaining high-performance solar energy systems.

Region	Average Humidity (%)
Algiers	66 - 82
Oran	59 - 83
Constantine	54 - 80
Aïn Sefra	31 - 69

Table (I.2): Average Humidity Levels in Selected Algerian Regions

I.5. Historical Development and Technological Advancements

The integration of photovoltaic (PV) systems with electrical grids has undergone significant evolution since Bell Labs developed the first practical solar cell in 1954 [5]. Below is a timeline of key milestones:

I.5.1.   First Grid-Connected Installations

The first grid-connected photovoltaic (PV) installations emerged in the 1970s–80s as experimental projects, signaling a shift toward integrating solar energy into mainstream power infrastructure. Early examples, such as the 6 kW system installed at the Massachusetts Institute of Technology (MIT) in 1978 and the 1 MW "Solar One" plant in California (1982), demonstrated the feasibility of feeding solar-generated electricity directly into the grid. These systems relied on improving but still costly silicon-based panels with efficiencies around 10%, making them economically uncompetitive without government or institutional support. Despite their limited scale and high upfront costs, these pioneering installations laid critical groundwork for policy frameworks, technical standards, and public awareness. They also spurred incremental advancements in efficiency and cost reduction, eventually enabling the exponential growth of grid-connected solar power in the 21st century.

I.5.2.   Smart Grids and Hybrid Systems
I.5.2.1. Smart grids

Smart grids are intelligent electrical networks that use digital technologies, IoT sensors, and real-time data analytics to optimize electricity generation, distribution, and consumption. They enable bidirectional communication between utilities and consumers, integrate renewable energy sources, manage storage and outages, and provide consumers with tools (like smart meters) for more efficient energy use. Essential for a sustainable energy transition, smart grids enhance reliability, reduce outages, and support decentralized, adaptive power systems.
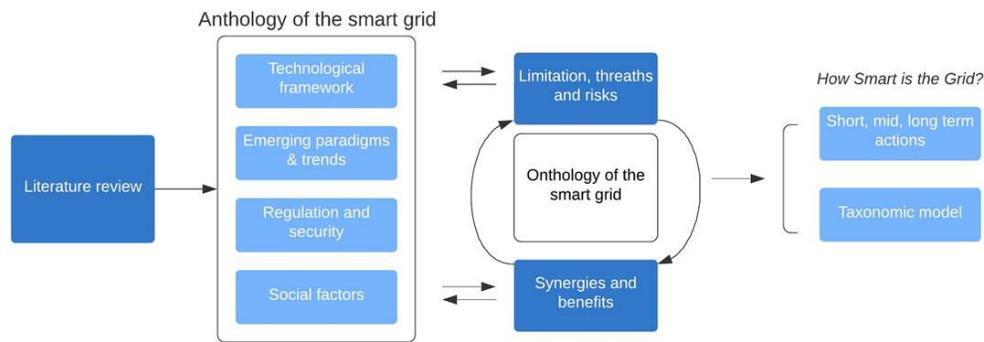
Figure (I.7): A Smart Grid integrates traditional electrical power systems

I.5.2.2. Hybrid Systems

Hybrid energy systems integrate renewable energy sources—like solar PV or wind—with conventional sources such as diesel generators or battery storage to ensure a reliable and stable electricity supply. These systems are particularly useful in areas with intermittent energy resources or limited grid access. A typical hybrid system combines solar panels, batteries for storage, and a backup generator, batteries covering shortfalls, and generators serving as a last resort.Hybrid systems enhance energy reliability, reduce fuel consumption, and lower environmental impact. Though their design requires careful analysis of local conditions and energy needs, they offer a practical and sustainable solution for many remote and off-grid locations.
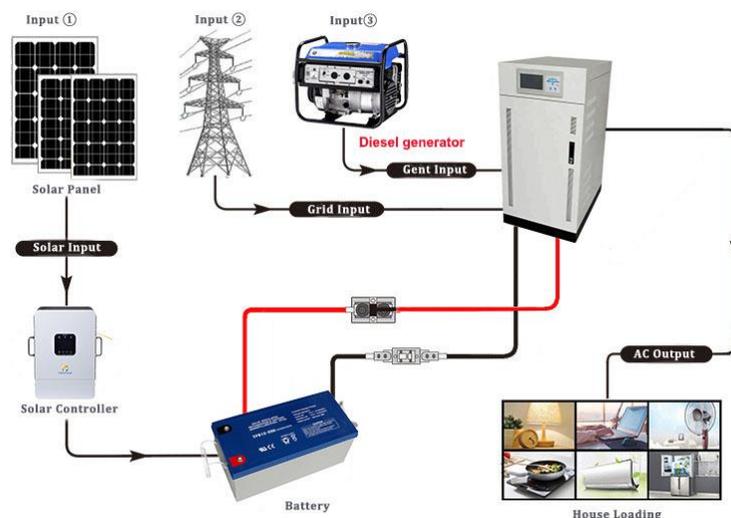
Figure (I.8): **Schematic Diagram of a Hybrid Energy System**

I.6. Photovoltaic Cell (PV)

I.6.1. Principle of a Photovoltaic Cell

A photovoltaic cell is a semiconductor device that generates electricity when exposed to light. It typically consists of a p-n junction, where sunlight induces charge separation, leading to electricity generation. The efficiency of a PV cell depends on factors such as material type, temperature, and light intensity [6]. The output current of a PV cell can be modeled using the diode equation:

$$I = I_{sc} - I_0 \left(e^{\frac{qV}{kT}} - 1 \right)$$ (I.1)

where:

- I is the output current (A),
- I_{sc} is the short-circuit current (A),
- I_0 is the reverse saturation current (A),
- q is the charge of an electron ($1.602 \times 10^{-19} C$),
- V is the output voltage (V),
- k is Boltzmann's constant ($1.381 \times 10^{-23} J/K$),
- T is the absolute temperature (K).

I.6.2. Photovoltaic Technology

First-generation solar cells are based on single P-N junctions using high-purity crystalline silicon. Their production is energy-intensive and costly due to the need for purified silicon and precise manufacturing. They are mainly divided into monocrystalline (high efficiency) and polycrystalline (lower cost, lower efficiency) types [09].

Monocrystalline Silicon Cell: For this type of application, pure silicon is obtained from quartz silica or sand through metallurgical chemical transformation. Monocrystalline silicon has an electrical efficiency and lifespan about twice that of amorphous silicon, but it is significantly more expensive. It is shown in Figure (I.4).

Figure (I.9): Monocrystalline Silicon Cell

➢ **Polycrystalline Silicon Cell:** Polycrystalline silicon is a material composed of juxtaposed crystals obtained through casting. This material is less expensive than monocrystalline silicon. The square or rectangular cells are easy to use, as shown in Figure (I.5).

Figure (I.10): Polycrystalline Silicon Cell

➢ **Second Generation Cells**

Thin-film (second-generation) solar cells [8] use materials like a-Si, CdTe, and CIGS deposited on surfaces such as glass. They are cheaper to produce and work well in low light and high temperatures,

But have **lower efficiency** (5–10%) and require more surface area [10].
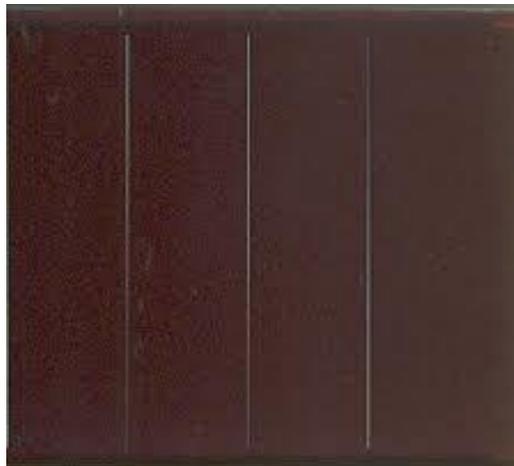
Figure (I.11):

Amorphous Silicon Cell (Thin Film)

> ➤ **third generation cells PERC/TOPCon**

PERC and TOPCon are advanced silicon solar cell technologies [6] that improve efficiency by reducing electron loss. PERC cells achieve over 22% efficiency, while TOPCon cells can exceed 24%. Both provide better performance, especially in hot conditions

Figure (I.12): Advanced PERC/TOPCon Solar Cell Structure

Technology	Efficiency	Advantages	Disadvantages
Monocrystalline Si	22–24%	High efficiency, long lifespan	High cost
Polycrystalline Si	15–18%	Lower cost	Lower efficiency
Thin-Film (CdTe)	10–12%	Lightweight, flexible	Shorter lifespan
PERC/TOPCon	24–26%	Enhanced light absorption	Complex manufacturing

Table I.3: Comparison of Solar Cell Technologies: Efficiency, Advantages, and Disadvantages

I.6.3. Efficiency of a Photovoltaic Cell

The efficiency η of a PV cell is defined as the ratio of the electrical power output to the incident solar power:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$ (I.2)

where:

- $P_{out} = V \times I$ is the electrical power output (W).
- $P_{in} = A \times G$ is the incident solar power, where:
- A = Area of the PV cell (m²)
- G = Solar irradiance (W/m^2)
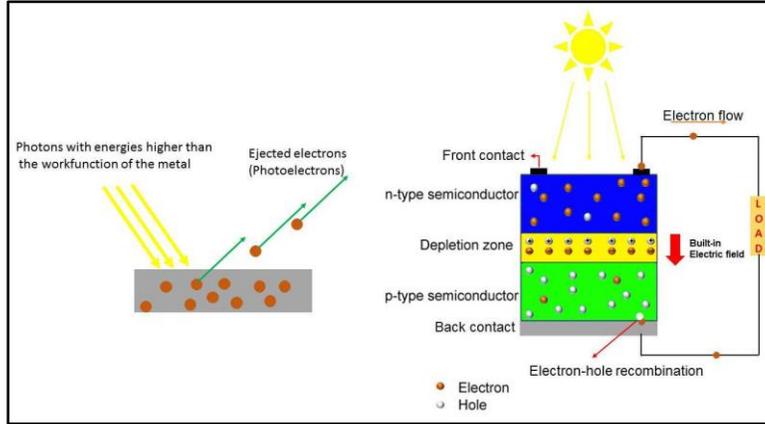
Figure (I.13): Principle of a Photovoltaic Cell

I.6.4.   Modeling of the Electrical Characteristics of a PV Cell

To understand and optimize the performance of photovoltaic (PV) cells, it is essential to develop an accurate electrical model that describes their behavior under different operating conditions. The modeling of PV cells is based on semiconductor physics and electrical circuit theory.

I.6.4.1. Single-Diode Model (Ideal PV Model)

The single-diode model is the most commonly used equivalent circuit representation of a PV cell. It consists of:

- A current source representing the photocurrent generated by sunlight.

- A diode that accounts for the p-n junction behavior.

- An internal series resistance R_s represents internal losses due to material resistance.

- A parallel (shunt) resistance R_{sh} models leakage current.

The Shockley diode equation gives the equation governing the output current of the PV cell:

$$I = I_L - I_0 \left(e^{\frac{q(V+IR_S)}{nkT}} - 1 \right) - \frac{V+IR_S}{R_{sh}}$$ (I.3)

where:

- I = Output current (A)
- I_L = Light-generated current (A)
- I_0 = Reverse saturation current (A)
- q = Electron charge ($1.602 \times 10^{-19} C$)
- V = Output voltage (V)
- R_s = Series resistance (Ω)
- R_{sh} = Shunt resistance (Ω)
- n = Ideality factor (typically between 1 and 2)
- k = Boltzmann's constant ($1.381 \times 10^{-23} J/K$)
- T = Temperature in Kelvin (K)

In an **ideal case**, where internal resistances are negligible ($R_s = 0$, $R_{sh} \rightarrow \infty$), the equation simplifies to:

$$I = I_L - I_0 \left(e^{\frac{qV}{nkT}} - 1 \right) \tag{I.4}$$
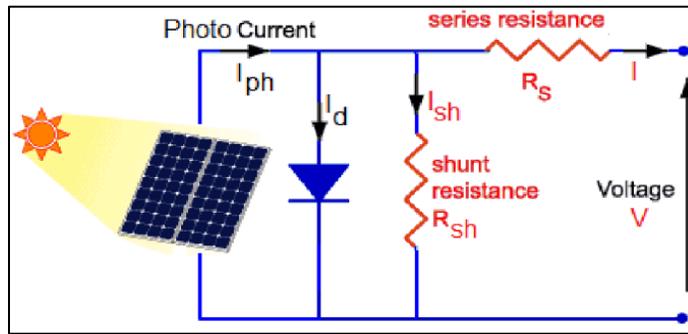
Figure (I.14) : PV cell equivalent circuit single-diode model

I.6.4.2. Current-Voltage (I-V) Characteristics

The behavior of a photovoltaic (PV) cell is typically characterized by its I-V curve, illustrating how the output current varies with voltage under varying levels of sunlight and temperature. Important parameters include:

Open-Circuit Voltage (V_{oc}): The maximum voltage when no current flows ($I = 0$).

$$V_{oc} = \frac{nkT}{q} \ln \left(\frac{I_L}{I_0} + 1 \right) \tag{I.5}$$

Short-Circuit Current (I_{sc}): The maximum current when the voltage is zero ($V = 0$) $I_{sc} \approx I_L$

Maximum Power Point (MPP): The operating point where the power output ($P = VI$) is maximized.

$$P_{max} = V_{mp} \times I_{mp} \tag{I.6}$$

Fill Factor (FF): given by:

$$FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}} \tag{I.7}$$

Efficiency (η): The ratio of the maximum power output to the incident solar power:

$$\eta = \frac{P_{max}}{P_{in}} \times 100\% \tag{I.8}$$
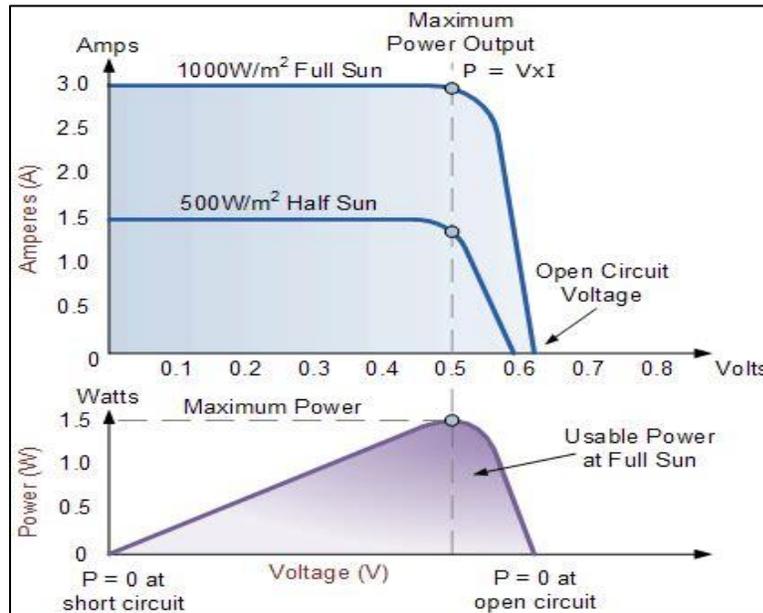
Figure (I.15) : I-V and P-V curves of a photovoltaic cell

I.6.4.3. Effect of Temperature and Irradiance

The performance of a photovoltaic (PV) panel is heavily influenced by **temperature** and **irradiance**. Higher **irradiance** (sunlight intensity) increases power output, as more photons generate greater current, making output nearly proportional to sunlight levels. However, **high temperatures** reduce efficiency by decreasing voltage, with power output typically dropping by **0.4–0.5% per** °C above standard conditions (25°C). While strong sunlight boosts production, excessive heat can offset gains, meaning PV panels often perform better in **cool, sunny climates** than in hot ones with similar irradiance. Optimal efficiency requires balancing these factors—maximizing sunlight exposure while minimizing heat buildup through proper panel ventilation and selecting materials with low temperature coefficients.

- **Increasing temperature** decreases V_{oc} and efficiency due to increased carrier recombination.
- **Increasing irradiance** increases I_{sc} and power output.
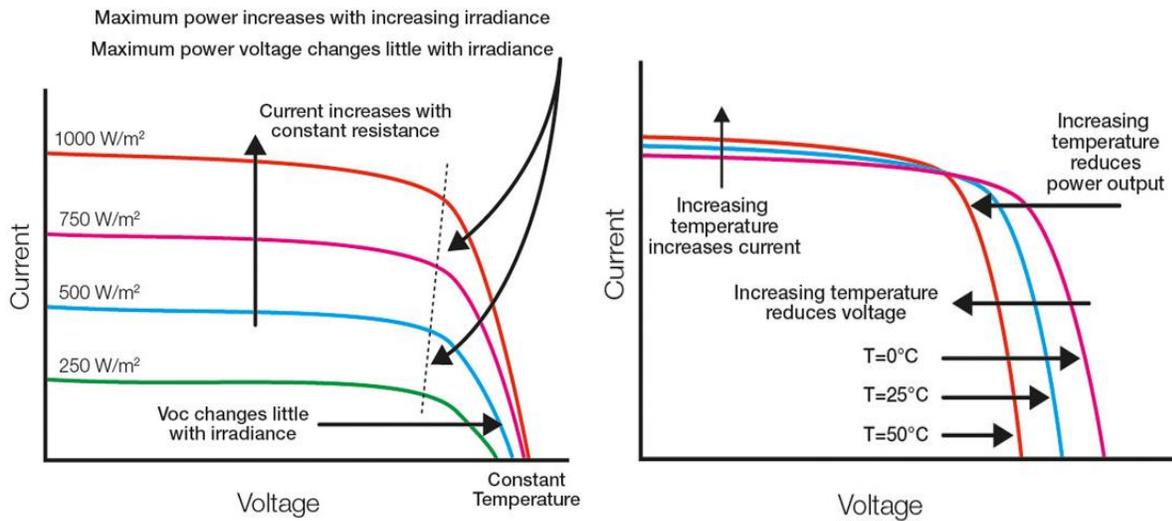
Figure (I.16): Effect of temperature and irradiance on PV cell performance

I.6.4.4. Effect of shading

Shading significantly reduces photovoltaic (PV) system performance by lowering current in shaded cells, causing power losses and potential damage like hot spots. The impact depends on shading extent, location, duration, and system design. Mitigation strategies include using bypass diodes, module-level power electronics, and optimizing panel placement and angles to avoid shade, ensuring better energy output and system reliability.
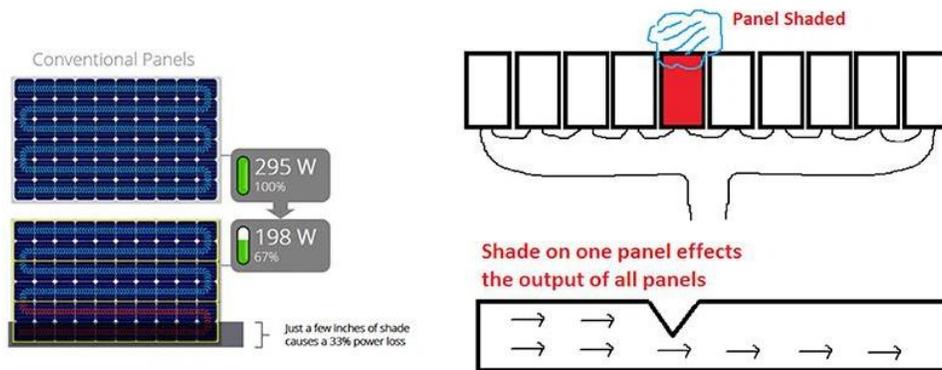
Figure (I.17): Effect of Partial Shading on the Output Characteristics of a Solar PV System
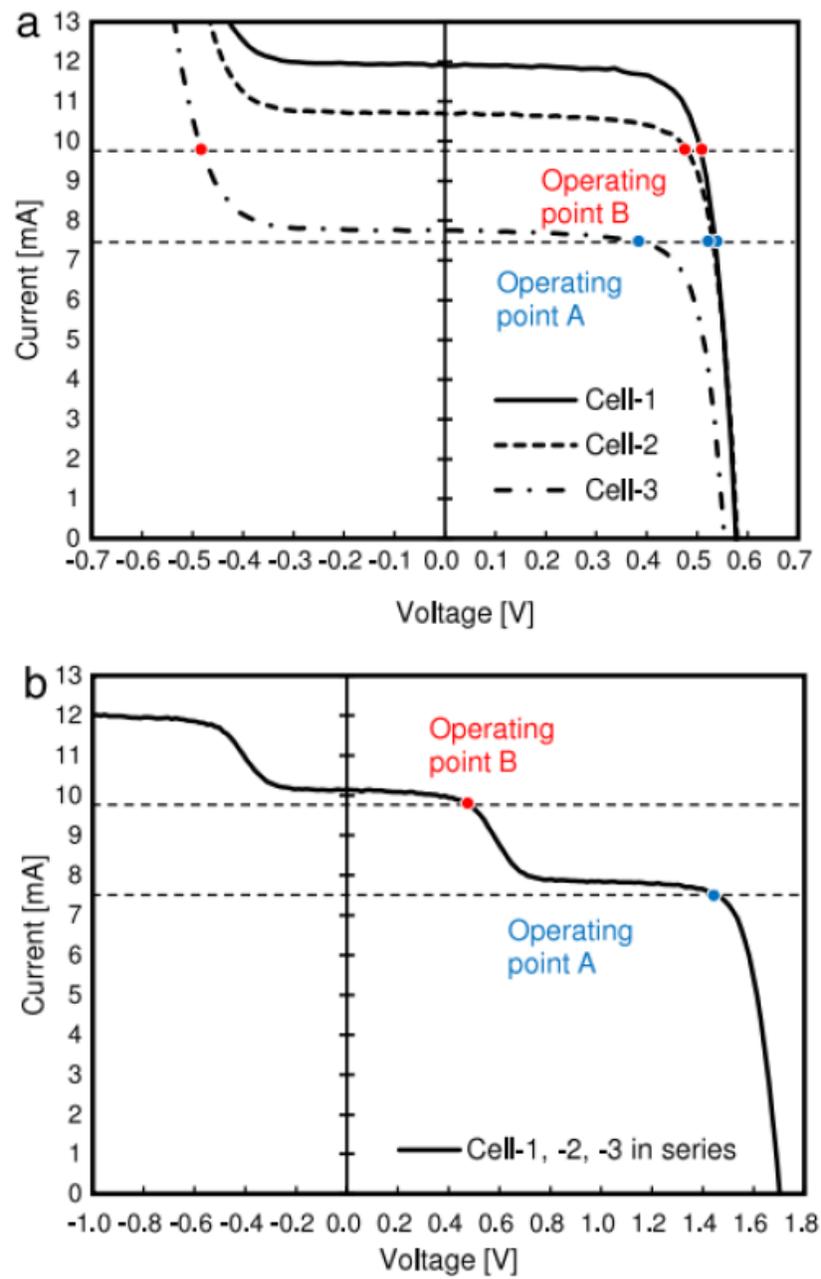
Figure (I.18): Current-Voltage Behavior Under Different Shading Conditions in a PV System

I.7. Solar Cell Innovations

Solar cell innovations recent innovations in solar cell technology have significantly enhanced efficiency, durability, and affordability. Among the most notable advancements are perovskite

solar cells, which offer high efficiency and low production costs. These materials are lightweight and flexible, making them ideal for integration into building materials and portable devices.

I.8. Different Configurations of PV Systems

Photovoltaic (PV) systems come in various configurations based on energy needs and grid access. Grid-tied systems connect directly to the utility without batteries, allowing net metering. Off-grid systems operate independently with battery storage for continuous power. Hybrid systems combine grid connection and batteries for backup and energy export. Other types include DC-coupled and AC-coupled systems, as well as solar-diesel hybrids for industrial use. Each setup balances cost, reliability, and energy independence according to user demands.

I.8.1.   On-Grid Photovoltaic (PV) Systems

An on-grid PV system is a solar power setup connected directly to the public electricity grid. It allows solar energy produced during the day to be used immediately, and any excess can be fed back into the grid. These systems are cost-effective, as they eliminate the need for batteries and can reduce electricity bills, especially in regions that offer net metering. However, they depend on the grid and cannot operate during a power outage unless combined with backup systems. Key components include solar panels, a grid-tied inverter, and protection equipment.
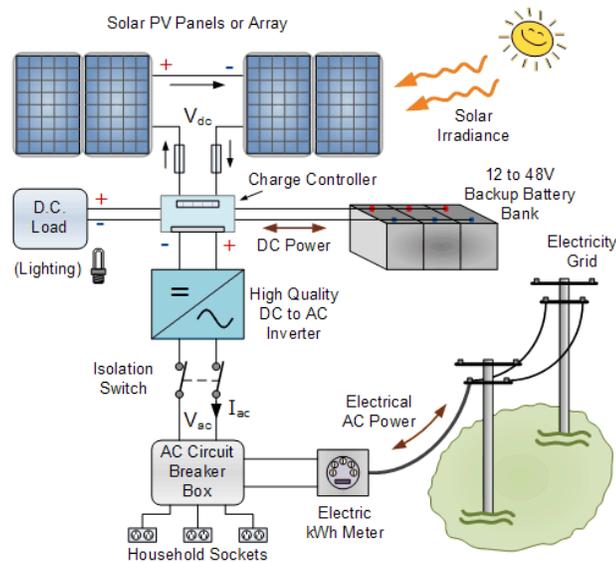
Figure (I.19): Schematic Diagram of a Grid-Connected PV System with Battery Backup

I.8.2. Off-Grid Photovoltaic (PV) System

An off-grid PV system operates independently of the public electricity grid. It is designed to supply power in remote areas where grid access is unavailable or unreliable. The system relies on solar panels to generate electricity, which is stored in batteries for use during the night or cloudy days. A charge controller regulates the battery charging process, while an inverter converts the stored DC electricity into AC for powering conventional appliances. Off-grid systems offer energy independence and are essential in rural electrification. However, they require oversizing to meet energy demand during low-sunlight periods and have higher initial costs due to the battery bank. Efficient energy management is crucial to avoid deep battery discharge or system downtime.
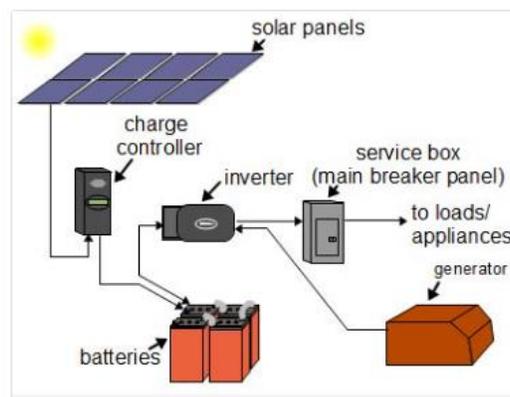
Figure (I.20): Basic Layout of an Off-Grid Solar Power System

FEATURE	ON-GRID PV SYSTEMS	OFF-GRID PV SYSTEMS
Grid Dependency	Requires grid connection; no power during outages.	Fully independent; uses batteries.
Energy Storage	Not required (excess power fed to the grid).	Requires batteries (Li-ion, lead-acid).
Cost	Lower upfront cost (no batteries).	Higher cost (batteries + charge controllers).
Maintenance	Minimal (no battery replacement).	High (battery lifespan ~5–10 years).
Scalability	Easily expandable.	Limited by battery capacity.
Applications	Urban areas, net-metering regions.	Remote locations, islands, emergency backup.

Table I.4: Comparative Analysis Between Off-Grid and On-Grid PV Systems

I.9. Conclusion

This introductory chapter laid the groundwork for understanding photovoltaic (PV) systems by exploring their historical evolution [4], working principles, types, and their growing role in the global energy transition. As solar energy continues to gain momentum due to its environmental, economic, and strategic advantages, mastering its technological foundations becomes increasingly crucial. The insights provided here not only contextualize the relevance of PV systems within modern energy systems but also pave the way for more in-depth technical and practical analysis in the following chapters. By establishing this background, we are now equipped to delve into the critical aspects of system design, simulation, and performance evaluation with a clear vision of both the potential and challenges of solar photovoltaic technology.

ChapterII : System Design and Performance Analysis

II.1. Introduction

This chapter presents the detailed sizing and configuration process of a residential   grid-connected photovoltaic (PV) system located in Ain Sefra, Algeria. The aim is to cover the daily electricity demand of a typical household, estimated at 28.8 kWh/day, using an efficient, cost-effective solar system without battery storage. The design considers solar resource availability, load estimation, selection of components, electrical safety, and financial and environmental impacts. The system is optimized for future integration with national net metering policies.

II.2. Overview of Solar Energy Potential and Project

Algeria possesses immense solar energy potential, particularly in southern regions like Ain Sefra, where solar irradiation exceeds 5.5 kWh [1]/m²/day. Despite this advantage, the country still relies on natural gas for over 98% of its electricity production. To shift toward a more sustainable energy model, Algeria launched the PNEREE program [2], aiming to install 15,000 MW of renewable capacity by 2035, including 13,575 MW from solar PV.

However, regulatory and infrastructure challenges remain, such as the lack of a nationwide net metering policy. In this context, a case study was conducted to design a residential grid-connected PV system in Ain Sefra. The system, sized at 7 kW using 18 monocrystalline [4] modules and a   7 kW inverter [6], is tailored to meet a daily energy demand of 28.8 kWh without storage.

The proposed PV system is expected to generate more energy than the household consumes, offering potential for grid injection. It could reduce CO_2 emissions by up to 7 tons annually and lower electricity bills by 80%, with a payback period of 5–7 years—demonstrating the viability of residential solar in Algeria.

II.3. Location Data of Aïn sefra

II.3.1.Orientation and Tilt Angle of Photovoltaic Panels

The orientation and tilt angle of photovoltaic (PV) panels are key design factors that significantly influence the efficiency and energy yield of a solar system. Proper alignment ensures maximum solar radiation absorption, thereby optimizing the system's performance and long-term reliability.
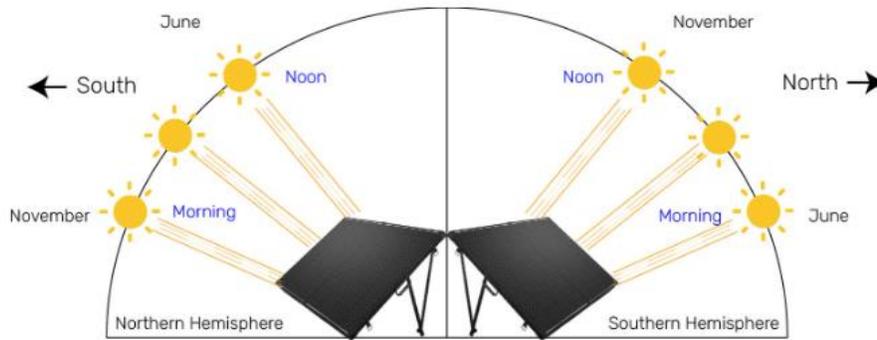
Figure (II.1) : Impact of Solar Panel Tilt Angle Based on Geographic Location: From North to South

II.3.1.1. Orientation (Azimuth Angle)

The **orientation**, also referred to as the **azimuth angle**, indicates the direction that the front surface of the solar panels faces. It is measured in degrees clockwise from **true north**, as follows:

- 0° corresponds to North
- 90° corresponds to East
- 180° corresponds to South
- 270° corresponds to West

In the **Northern Hemisphere**, and particularly in Algeria, the optimal orientation for solar panels is due **south (180°)**, as this position ensures maximum solar exposure over the entire year. Therefore, for the site in **Aïn Sefra**, a due south orientation is recommended.
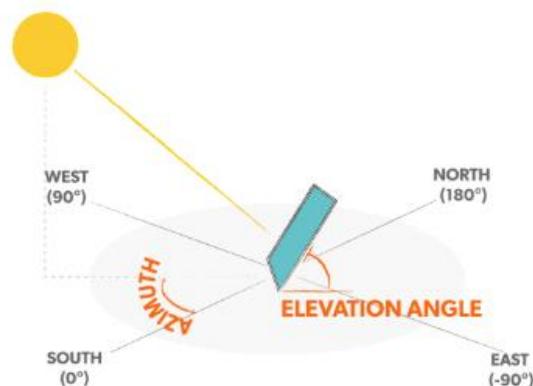
Figure (II.2) : Tilt and azimuth angle in relation

II.3.1.2. Tilt Angle (Inclination)

The **tilt angle** refers to the angle between the PV panel and the horizontal ground surface. This angle determines the amount of sunlight that directly strikes the panel throughout the year. A general rule of thumb is to set the tilt angle equal to the **latitude** of the installation site.

Equation II.1 shows the relationship:

$$\theta_{tilt} \approx \phi \tag{II.1}$$

Where:

- θ_{tilt} = Optimal tilt angle (in degrees)
- ϕ = Latitude of the installation site (in degrees)
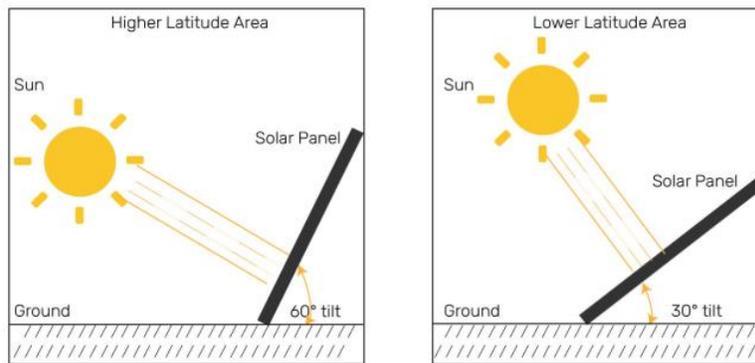
Figure (II.3) : Optimal Tilt Angle of Solar Panels Relative to Latitude

For **Aïn Sefra**, with a latitude of approximately **32° N**, the ideal tilt angle for fixed panels would be between **30° and 35°**. This range ensures that the panels receive optimal exposure to sunlight and maximize energy production throughout the year.

In some cases, the tilt angle can be adjusted seasonally to further optimize energy production during specific times of the year. The following adjustments can be made:

- **Winter optimization:**

$$\theta_{tilt} = \phi + 10° \text{ to } 15° \Rightarrow 42°–47°$$

- **Summer optimization:**

$$\theta_{tilt} = \phi - 10° \text{ to } 15° \Rightarrow 17°–22°$$

These seasonal adjustments are beneficial for PV systems that experience significant variations in energy demand throughout the year or for systems with adjustable mounting structures.

II.3.1.3. Summary of Recommended Parameters

The following table summarizes the recommended orientation and tilt angles for the site of **Aïn Sefra**:

Parameter	Recommended Value
Orientation (Azimuth Angle)	Due South (180°)
Latitude of Aïn Sefra	Approximately 32° N
Optimal Fixed Tilt Angle	30° – 35°
Winter Tilt Adjustment	42° – 47°
Summer Tilt Adjustment	17° – 22°

Table (II.1): orientation and tilt angles for the site of Aïn Sefra

This analysis confirms that a south-facing orientation and a tilt angle that aligns with the latitude of Aïn Sefra will ensure optimal solar energy capture year-round. These settings will help minimize performance losses and enhance system durability, particularly in the semi-arid conditions of the region.

II.3.2.Solar Irradiance

Aïn Sefra demonstrates excellent solar potential, making it an ideal location for the deployment of photovoltaic (PV) systems. The analysis of local solar irradiance data highlights the region's strong suitability for both residential and utility-scale solar energy projects.

- **Global Horizontal Irradiance (GHI):** The average GHI in Aïn Sefra is approximately **5.1 kWh/m²/day**. This value reflects the total amount of solar energy received on a horizontal surface daily, indicating strong potential for stable, year-round PV electricity production.

- **Direct Normal Irradiance (DNI):** During peak summer months, DNI reaches about **6.0 kWh/m²/day**. This value is particularly important for solar tracking systems and concentrated solar power (CSP) technologies, as it measures the intensity of direct sunlight on a surface perpendicular to the sun's rays.

- **Diffuse Horizontal Irradiance (DHI):** The DHI in Aïn Sefra averages **1.1 kWh/m²/day**, which is relatively low. This means the region has clear skies with minimal atmospheric scattering, allowing for more efficient performance of PV systems that depend on direct sunlight.

These irradiance values confirm that Aïn Sefra offers optimal conditions for solar energy production. The combination of high GHI and DNI, alongside low DHI, ensures high energy yields and improved economic returns for solar installations in the region.

Irradiance Type	Value (kWh/m²/day)
Global Horizontal Irradiance (GHI)	5.1
Direct Normal Irradiance (DNI)	6.0
Diffuse Horizontal Irradiance (DHI)	1.1

Table (II.2): Solar Irradiance Data for Aïn Sefra
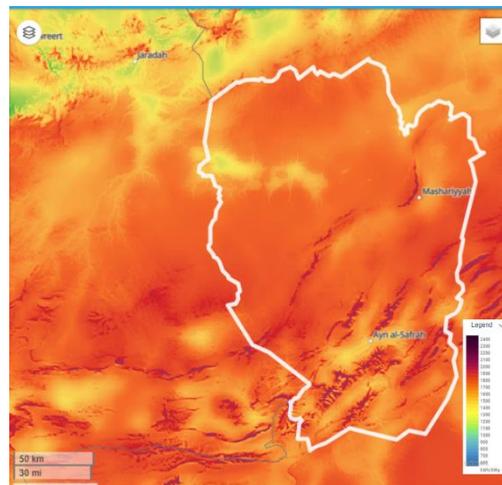
Figure (II.4) : solar irradiance data for Aïn Sefra
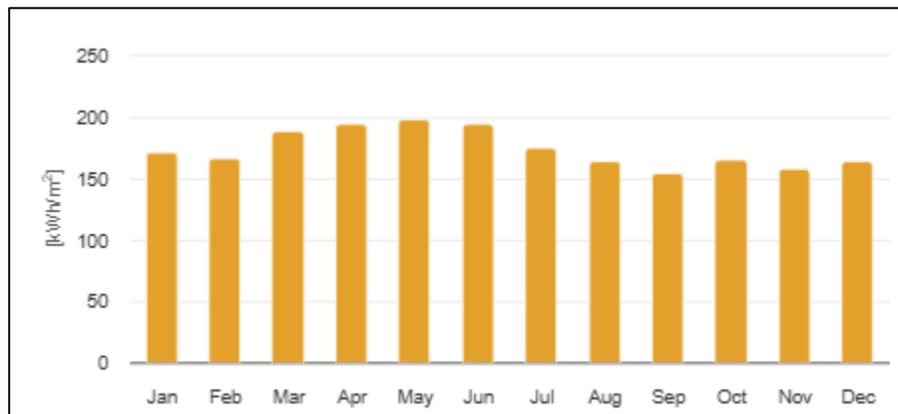
Figure (II.5) : Monthly averages Direct normal irradiation for Aïn Sefra

II.3.3. Temperature & Weather

To accurately assess the performance and reliability of photovoltaic (PV) systems, it is essential to evaluate the prevailing climatic conditions of the selected site. Climatic factors, particularly temperature profiles and weather phenomena, exert a direct influence on the efficiency, longevity, and maintenance requirements of solar installations. The following analysis provides an overview of the temperature patterns and weather characteristics specific to Aïn Sefra, offering crucial insights for the optimal design and operational management of the PV system.

Climate Factor	Value
Average Annual Temperature	25°C (Approx.)
Summer Maximum Temperature	45°C
Rainfall (Annual)	~100 mm/year
Wind Speed	10 - 15 km/h (Average)
Dust Storm Frequency	High in summer months

Table(II.3): Climatic Data for Aïn Sefra

Aïn Sefra experiences a semi-arid climate characterized by generally mild to cold winters, where nighttime temperatures can drop significantly, and moderately hot summers with occasional peaks in temperature. These climatic conditions, marked by low humidity and high solar availability, create a favorable environment for the installation and efficient operation of photovoltaic (PV) systems throughout the year.

- **Moderate Temperatures:** The region's average annual temperature ranges between **18°C and 22°C**. Summer temperatures occasionally rise above 35°C but remain moderate compared to extreme desert climates. In winter, temperatures can drop significantly, especially at night.

- **Favorable Solar Irradiance:** Aïn Sefra benefits from high levels of solar radiation throughout the year, particularly in summer when skies are mostly clear. This contributes to consistent and efficient solar energy generation.

- **Low Cloud Cover:** Minimal cloudiness across the year ensures a high proportion of direct sunlight, which is ideal for fixed PV systems and enhances overall system performance.

- **Dust and Sand Considerations:** Occasional dust or sandstorms, especially in spring, may affect PV panel cleanliness and efficiency. Regular maintenance and cleaning are necessary to minimize energy losses caused by soiling.
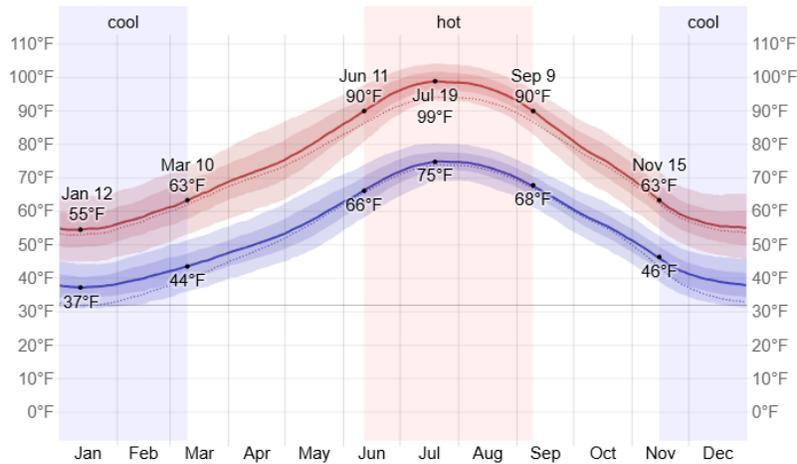
Figure (II.6) : Average High and Low Temperature in Aïn Sefra
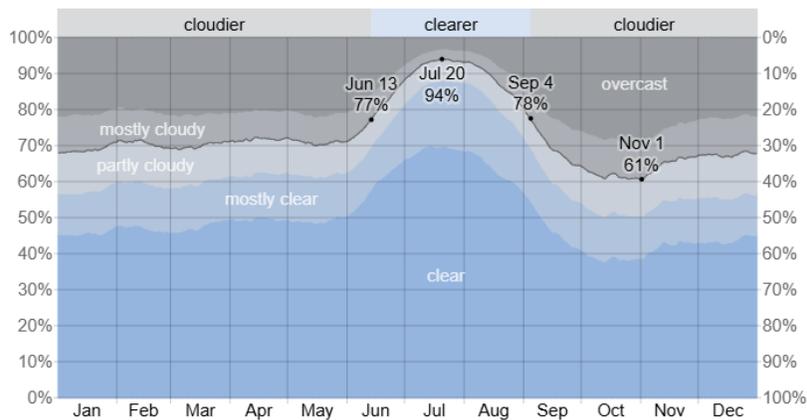
Figure (II.7) : Cloud Cover Categories in Aïn Sefra

II.4.   On-Grid PV System Sizing and Component Selection

The design of an on-grid photovoltaic (PV) system requires a careful balance between energy needs, available solar resources, and technical specifications to ensure efficiency, reliability, and cost-effectiveness. The main objective is to determine the appropriate system size and components capable of supplying sufficient energy to meet the local consumption demand while integrating seamlessly with the electrical grid.
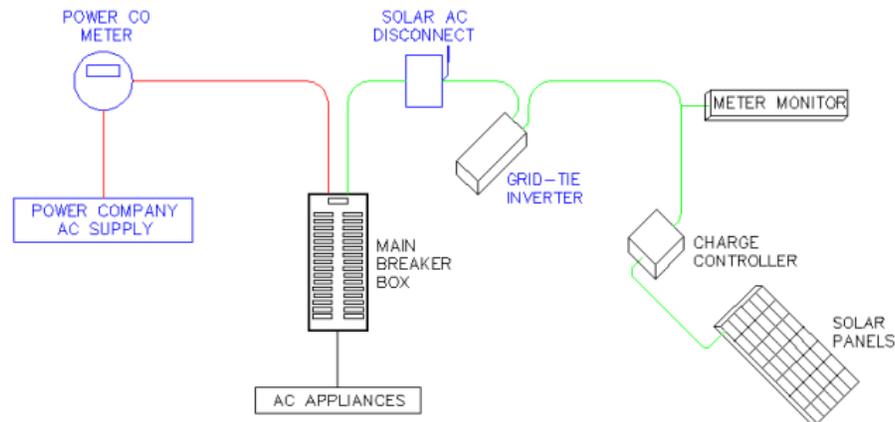
Figure (II.8) :Basic Grid-Tie System design

– System Sizing

The system must be dimensioned based on key parameters such as:

- **Solar irradiance** and **ambient temperature** at the installation site,
- **Electrical load profile**, including daily and seasonal consumption,
- System losses, including thermal, wiring, and inverter [6] losses.

Proper sizing ensures the PV system generates adequate electricity without unnecessary oversizing, which can increase costs without significant benefit.

– Key Components

- ➢ **Photovoltaic Modules**: These are responsible for converting sunlight into direct current (DC) electricity. Their performance depends on factors such as module efficiency, temperature coefficient, and orientation.

- ➢ Inverter: The inverter [6] converts DC electricity generated by the modules into alternating current (AC) suitable for grid use. It must be selected based on the maximum system power output and should comply with grid voltage and frequency standards.

> ➢ **Grid Connection Equipment**: This includes protective devices, bidirectional meters, and interface units ensuring safe and accurate energy transfer between the PV system and the utility grid.

– Component Selection Criteria

Component selection should consider:

- **Module efficiency and durability**, especially under local climatic conditions.
- **Inverter capacity**, with the ability to handle peak power and integrate with the grid.
- **Compliance with local electrical codes** and **grid-tie requirements**.

PV Modules   **Inverter & Electronics**

Charge Controller   **Solar Array Mounting System**   **Cables & Connectors**

Figure (II.8) : PV System Components

– Tilt Angle and Orientation

The **tilt angle** and **orientation** of PV panels directly influence the energy capture:

- The **optimal tilt angle** is generally close to the **latitude** of the location to maximize annual energy production.
- **South-facing orientation** is preferred in the Northern Hemisphere, while **north-facing** is ideal in the Southern Hemisphere.
- Seasonal adjustments or sun-tracking systems may be used to further optimize yield.

– Electrical Design Considerations

Efficient electrical configuration involves:

- **Proper string and array sizing**,

- **Minimization of shading** and mismatch losses,

- Use of power optimizers or microinverter [6]s where necessary,

- Accounting for **voltage drops** and **degradation rate** of modules over time.

– Grid Integration

For seamless integration:

- The system must meet **local utility standards** for voltage, frequency, and safety.

- A **bidirectional energy meter** is installed to measure electricity inflow and outflow.

- **Net metering policies** may allow users to earn credits for excess energy supplied to the grid.

II.4.1.Load Profile Estimation

This study focuses on designing a grid-connected photovoltaic (PV) system for a typical two-story residential house in Ain Sefra, southwestern Algeria, which has high solar irradiance levels, making it ideal for solar energy production. The house, housing an average family, has an estimated daily energy consumption of approximately 28.8 kWh, based on typical household appliances.

The design process considers two key factors:

- ➢ **Daily energy demand** (kWh/day), which guides the PV array sizing.
- ➢ Peak power demand (6 to 7 kW), important for selecting the appropriate inverter [6] size to handle maximum load.

The PV system is designed to offset between 70% and 100% of the household's electricity consumption, depending on seasonal variations and net metering rules in Algeria. This system aims to reduce reliance on the grid, lower electricity bills, and allow for potential energy credits during surplus production.

A table detailing the key electrical appliances and their contributions to daily energy demand follows for better understanding.

Appliance	Power (W)	Quantity	Hours/Day(h)	Daily Energy Consumption (kWh)
Lighting	20	22	5	**2.2**
Refrigerator	150	2	24	**7.2**
TV	100	2	4	**0.8**
Air Conditioner	1500	2	3	**9.0**
Washing Machine	500	2	1	**1.0**
Water Heater	2000	2	1	**4.0**
Computer/Laptop	100	2	3	**0.6**
Fans	75	4	6	**1.8**
Microwave	1200	2	0.5	**1.2**
Total				**27.8 kWh/day**

Table(II.4): Daily Energy Consumption of Household Appliances in a Two-Story Residential House in Ain Sefra

II.4.1.1. About Solar Panel

In this study, the Sunpro SP400-144MG monocrystalline [4] photovoltaic module has been selected for its high efficiency, robustness, and suitability for residential applications in sun-rich regions such as Ain Sefra. With a rated power output of 400 W and a module efficiency of 19.88%, this panel offers reliable performance even under partial shading or high-temperature conditions, which are common in the region. Its half-cut cell technology and PERC (Passivated Emitter Rear Cell) structure enhance both durability and energy yield. These features make the Sunpro panel a suitable choice for a two-story residential house with a daily energy consumption of approximately 28.8 kWh. The table below presents the technical characteristics of the selected module, which will serve as a reference for further system sizing and performance estimation.

Specification	Details
Model	Sunpro SP400-144MG
Power Output (Pmax)	400 W
Efficiency	19.88%
Cell Type	Monocrystalline (Half-cut, PERC)
Number of Cells	144 (6×24)
Voltage at Max Power (Vmp)	40.67 V
Current at Max Power (Imp)	9.84 A
Open-Circuit Voltage (Voc)	48.73 V
Short-Circuit Current (Isc)	10.38 A
Dimensions ($L \times W \times H$)	2008 mm $\times$ 1002 mm $\times$ 35 mm
Weight	22.0 kg
Junction Box	IP68, MC4 Compatible
Max System Voltage	1500 V DC
Wind/Snow Load	2400/5400 Pa
Warranty	12 years product, 25 years performance
Estimated Price	60–104 USD

Table(II.5): Technical Specifications of Sunpro SP400-144MG Solar Panel

Figure (II.9) : images of the **Sunpro SP400-144MG** solar panel

II.4.2.PV Array Sizing

This section presents the technical sizing of the proposed on-grid photovoltaic (PV) system for a residential application located in Aïn Sefra, Algeria. The system is designed to meet the daily energy needs of a typical two-story household, with an average daily consumption of 28.8 kWh. The methodology applied here follows standard international engineering practices and is adapted from the reference approach presented in similar feasibility studies.

o ensure optimal solar energy harvesting, the PV modules must be oriented and inclined properly. In the Northern Hemisphere, modules should face due south for maximum year-round exposure. Furthermore, the tilt angle should ideally match the site's latitude. Aïn Sefra is located at approximately 33.3° N, and thus the panels in this project are set at a fixed tilt angle of 33°, as illustrated in Equation (II.1).

$$\text{Tilt}_{\text{angle}} = \text{Latitude} = 33.3°$$ **(II.2)**

This configuration ensures a balanced annual energy yield without the need for a solar tracking system.

II.4.2.1. Daily Energy Demand

The total energy demand is derived from the aggregated use of standard home appliances, with daily consumption estimated around 28.8 kWh/day. This results in an annual energy requirement calculated as:

$$E_{\text{daily}} = 27.8 \text{ kWh/day}$$ **(II.3)**

To ensure a more flexible system, we perform the following calculation:

$$E_{\text{daily}} = 27.8 \times 1.01 = 28.8 \text{ kWh/day}$$ **(II.4)**

II.4.2.2.   PV Power Calculation

To determine the required photovoltaic capacity that can supply the household's demand, we consider both the performance ratio (PR) and the average solar irradiance for Aïn Sefra. The PR is a coefficient that represents real-world energy losses due to various factors, including module temperature, wiring, inverter

[6] efficiency, dust accumulation, and mismatch losses. A PR of 0.75 is commonly used for grid-connected systems in semi-arid regions.

The average **global horizontal irradiance (GHI)** in Aïn Sefra is approximately **5.5 kWh/m²/day**. Using this value, we calculate the required PV capacity based on the following equation:

$$P_{PV} = \frac{E_{annual}}{PR \times G \times 365} \tag{II.5}$$

Substituting the known values:

$$P_{PV} = \frac{28.8}{0.75 \times 5.5} \approx 7 \text{ kWp} \tag{II.6}$$

For design safety and to accommodate any future system expansion or degradation, we round this up to **7 kWp** as the nominal installed capacity.

II.4.2.3.   Annual Energy Demand

Thus, the annual energy demand is calculated as:

$$E_{annual} = 28.8 \times 365 = 10.51 \text{ MWh/yea} \tag{II.7}$$

II.4.2.4.   Solar Resource and System Efficiency

The solar resource at the site of Ain Sefra is characterized by the following parameters:

- **Global Horizontal Irradiance (GHI)**: 5.5 kWh/m²/day

- Performance Ratio (PR): 0.75 (this accounts for system losses due to temperature variations, dust, wiring, inverter [6] inefficiencies, and other factors).

II.4.2.5.   Required PV Power Calculation

The required installed PV capacity is calculated using the following formula:

$$P_{PV} = \frac{E_{annual}}{PR \times GHI \times 365} \tag{II.8}$$

Substituting the known values:

$$P_{PV} = \frac{10,51}{0.75 \times 5.5 \times 365} \approx \boxed{7 \text{ kWp}} \tag{II.9}$$

To allow for performance degradation and potential future increases in energy demand, the required system capacity is rounded to:

$$P_{PV} = \boxed{7 \text{ kWp}} \tag{II.10}$$

II.4.2.6.   PV Module Selection

The selected PV module is a high-efficiency monocrystalline [4]

Based on the required system capacity of 7.6 kWp, the number of modules needed is calculated as:

$$N_{modules} = \frac{P_{PV}}{P_{module}} = \frac{7000}{400} = 17.5 \approx \boxed{18 \text{ modules}} \tag{II.11}$$

II.4.2.7.   Electrical Configuration

To ensure optimal inverter [6] performance and safety, the 18 PV modules will be distributed across two strings, each connected to an independent Maximum Power Point Tracking (MPPT) input of the inverter [6]. The electrical configuration for each string is as follows:

- **String 1**: 9 modules in series

$$V_{string1} = 9 \times 40.67 \text{ V} = 366.0 \text{ V} \tag{II.12}$$

- **String 2**: 9 modules in series

$$V_{string2} = 9 \times 40.67 \text{ V} = 366.0 \text{ V} \tag{II.13}$$

Each string will produce an approximate current of 9.84 A, ensuring that both strings are compatible with the inverter [6]'s MPPT inputs. This configuration ensures optimal power tracking and reduces the impact of mismatch between the strings.

II.4.2.8.   Peak Power of the System

The peak power of the PV system is calculated by multiplying the rated power of each module by the total number of modules:

$$\mathbf{P_{peak} = N_{modules} \times P_{module} = 18 \times 400 \text{ Wp} = 7.2 \text{ kWp}} \approx P_{PV} \tag{II.14}$$

II.4.2.9.   System Voltage

The system voltage V_{system} is determined by the highest voltage produced by the two strings, as they are connected in parallel. Since the voltage in each string is different, the system voltage will be equal to the voltage of the higher voltage string:

$$V_{\text{system}} = V_{\text{string}} = 366 \text{ V} \qquad \textbf{(II.15)}$$

II.4.2.10.   Summary of Sizing

The following table summarizes the key parameters of the PV array sizing:

Parameter	Value
Daily Energy Demand	28.8 kWh/day
Annual Energy Demand	10,51 kWh/year
Required PV Capacity	7 kWp
Selected Module Capacity	400 Wp
Number of PV Modules	18
String Configuration	2 string
String Voltages	366 V
String Current (Approximate)	9.84 A each
Inverter Input Configuration	Dual MPPT inputs
Peak Power of the System	7 kWp

Table (II.6) : key parameters of the PV array sizing

II.4.3.   Inverter Sizing

The inverter [6] is a crucial component in a grid-connected PV system, responsible for converting the direct current (DC) generated by the PV array into alternating current (AC) suitable for grid injection. Proper inverter [6] sizing ensures optimal energy yield, system safety, and cost-effectiveness.

II.4.3.1.   Inverter Sizing Criteria

When selecting an appropriate inverter [6] for the system, the following technical criteria must be considered:

- **Rated AC power** should closely match (or slightly undersize) the total DC array power.

- **MPPT voltage range** must encompass the string voltage ranges.

- **Maximum DC input voltage** must be higher than the maximum possible string voltage.

- **Maximum DC current per MPPT** must support current from each string.

- **Dual MPPT inputs** are required to accommodate the two unequal strings.

II.4.3.2.   Inverter Power Rating

The PV array's total DC peak power is:

$$P_{DC} = 18 \times 400 = 7.2 \text{ Wp} \tag{II.16}$$

In general, the inverter [6]'s AC power is chosen between 90% and 110% of the array power. For this project, we consider a slight undersizing to reduce cost while maintaining efficiency:

$$P_{AC,inverter} \approx 0.95 \times P_{DC} = 0.95 \times 7.2 = \boxed{6{,}84 \text{ W}} \tag{II.17}$$

Thus, a 7 kW three-phase inverter [6] is selected.

II.4.3.3.   Voltage and Current Matching

We must verify that the selected inverter [6] supports the string voltages and currents:

- **String voltages**:

$$V_{string1} = V_{string2} = 366 \text{ V} \tag{II.18}$$

- **Inverter MPPT voltage range**: must include 366 V (e.g., 200–800 V acceptable range)

- **String current**:

$$I_{string} \approx 9.84 \text{ A} \tag{II.19}$$

- **Inverter max input current per MPPT** ≥ 10 A

- **Inverter max DC voltage** > open-circuit voltage of the strings (calculated in the next section)

II.4.3.4.   Open-Circuit Voltage Check (Temperature Consideration)

The open-circuit voltage V_{oc} of each module increases at low temperatures. Assuming:

- **Module V_oc at STC**: 49.8 V

- **Temperature coefficient**: −0.28%/°C

- **Lowest ambient temp in Ain Sefra**: −2 °C

- **Nominal cell temp**: 25 °C

Then the corrected V_oc per module is:

$$\mathbf{V_{oc,corrected} = 49.8 \times [1 + (-0.0028 \times (-2 - 25))] = 49.8 \times 1.0756 \approx 53.5\ V}$$

(II.20)

Hence, the maximum string voltages:

- **9-module string**:

$$V_{oc,string2} = 9 \times 53.5 = \boxed{481.5\ V} \qquad \textbf{(II.21)}$$

These values must be lower than the inverter [6]'s max DC input voltage (typically 600–1000 V).

II.4.3.5.   Selected Inverter Specifications

Based on the criteria above, the following inverter [6] model is proposed:

Parameter	Value
Inverter Model	Huawei SUN2000-7KTL
Rated AC Power	7 W
MPPT Voltage Range	200–850 V
Max DC Voltage	1 V
Max DC Input Current (per MPPT)	11 A
Number of MPPT Inputs	2
Efficiency	98.6%

Table (II.7): Selected Inverter Specifications

II.4.3.6.   Cable Sizing and Electrical Loss Considerations

Proper cable sizing is essential to ensure the safety, efficiency, and longevity of a photovoltaic (PV) system. In grid-connected systems, cables must be selected based on the system voltage, current flow, permissible voltage drop, and installation environment. In this study, both DC cables (between PV modules and inverter

[6]) and AC cables (between inverter [6] and distribution panel) are sized according to international standards such as IEC 60364 and IEC 62548 [9].

II.4.3.6.1.   DC Cable Sizing (PV Modules to Inverter)

- **System Configuration**: 2 strings of 9 modules and 1 string of 10 modules
- **Module Current (Imp)**: 9.84 A
- **Max Current per String (Istring)**: ≈ 10 A
- **Cable Type**: Copper, solar-grade, UV-resistant
- **Distance (1-way length)**: assumed 15 meters
- **Voltage Drop Limit**: <1.5% of DC voltage (typically 600–1000 V)

Using the voltage drop formula:

$$S = \frac{2 \times L \times I}{\gamma \times \Delta V} \tag{II.22}$$

Where:

- S = cross-sectional area (mm²)
- L = one-way cable length (m)
- I = current (A)
- γ = conductivity of copper (~56 m/Ω·mm²)
- ΔV = allowed voltage drop (V)

Assuming a 1.5% drop of 600 V:

$$\Delta V = 0.015 \times 600 = 9V \tag{II.23}$$

$$S = \frac{2 \times 15 \times 10}{56 \times 9} \approx 0.6 \text{ mm}^2 \tag{II.24}$$

For safety and temperature derating, a **minimum of 4 mm²** DC cables is recommended, and **6 mm²** is commonly used in practice for robustness and future-proofing.

II.4.3.6.2.   AC Cable Sizing (Inverter to Main Panel)

- **Inverter Power Output**: 7 kW
- **Voltage**: 230 V AC (single-phase assumed)
- **Current**:

$$I = \frac{P}{V \times \cos\phi} = \frac{7000}{230 \times 0.9} \approx 29A \tag{II.25}$$

Assuming a 20 m cable run and 1.5% voltage drop:

$$\Delta V = 0.015 \times 230 = 3.45V \tag{II.26}$$

$$S = \frac{2 \times 20 \times 29}{56 \times 3.45} \approx 6mm^2 \tag{II.27}$$

Thus, a **minimum 6 mm² copper cable** is required. In installations subject to higher temperatures or longer distances, **10 mm²** may be used to reduce losses.

Cable Type	Location	Recommended Size
DC Cable (String)	PV modules to inverter (DC)	4–6 mm²
AC Cable	Inverter to main panel (AC)	6–10 mm²
Grounding Cable	Module frames and inverter	≥ 6 mm² (green/yellow)

Table (II.8) : Summary of Cable Recommendations

II.5. Balance of System (BOS)

The Balance of System (BOS) encompasses all components of a photovoltaic system aside from the photovoltaic modules and the inverter [6]. These components are essential to ensure the safe, efficient, and reliable operation of the system. BOS elements play a vital role in energy transmission, structural stability, system protection, and monitoring.

II.5.1. Major BOS Components

The BOS for the grid-connected PV system includes:

1. Mounting Structure

- Supports PV modules securely and maintains their optimal orientation and tilt.
- In this project, an **aluminum ground-mounted frame** with a tilt angle of **30°**, aligned toward the south, is selected to maximize solar gain.
- The structure is designed to withstand local wind and snow loads in Ain Sefra.

2. DC Cabling and Connectors

- **High-quality copper cables** with UV resistance and appropriate cross-sectional area (typically 4–6 mm²) are used to minimize voltage drop.
- **MC4 connectors** ensure waterproof, reliable DC connections between modules and strings.

3. Combiner Box (if applicable)

- In systems with more than two strings, a **combiner box** merges multiple DC inputs into one or more outputs.

- In this design, since each string is connected to a dedicated MPPT input, a combiner box is not mandatory but may be used for centralized protection.

4. Protection Devices

- **DC side protections**:

    o **Fuses** or **circuit breakers** for overcurrent protection.

    o **Surge Protection Devices (SPD)** to guard against voltage spikes.

    o **DC disconnect switch** for safe maintenance.

- **AC side protections**:

    o **AC circuit breakers**, **SPD**, and **residual current devices (RCDs)** to ensure grid and personnel safety.

5. Grounding System

- A proper **earthing system** is critical to protect against electric shock and equipment damage.

- All metallic parts and DC negative terminals are grounded in compliance with international safety standards (e.g., IEC 60364, IEC 61730).

6. Monitoring and Data Logging

- The inverter [6] integrates a monitoring system via Wi-Fi or Ethernet, enabling real-time tracking of system performance, power output, and fault detection.

7. Utility Metering

- A **bidirectional meter** is installed to measure both energy injected into the grid and energy consumed from it.

- This supports net-metering or feed-in-tariff schemes, if applicable.

II.5.2.Estimated BOS Cost Share

While exact prices depend on supplier and location, BOS components typically account for **30–40%** of the total system cost. A breakdown is provided in **Table II.9**

Component	Estimated Share (%)
Mounting structure	10–12
Cables and connectors	5–7
Protection devices (DC/AC)	5–8
Monitoring system	3–5
Grounding and accessories	2–4
Installation labor/tools	5–10
Total BOS share	**30–40%**

Table (II.9) Estimated BOS Component Share

II.6. Grid Integration and Compliance

Integrating a photovoltaic (PV) system into the national electricity grid requires both regulatory authorization and technical conformity. One of the key mechanisms facilitating such integration, especially for small-scale residential and commercial users, is **net metering**, which enables the bidirectional exchange of energy between consumers and the grid.

II.6.1. Definition of Net Metering and Comparison with Gross Metering

Net metering is a policy mechanism that allows solar PV system owners to offset their electricity consumption by exporting surplus energy back to the grid. A bidirectional meter records both the energy imported from and exported to the grid. At the end of a billing cycle, consumers are billed only for their **net consumption** (i.e., energy imported minus energy exported).

In contrast, **gross metering** records all the energy generated by the PV system and all energy consumed from the grid separately. The electricity fed into the grid is typically compensated at a predefined tariff, independent of the consumer's energy usage.
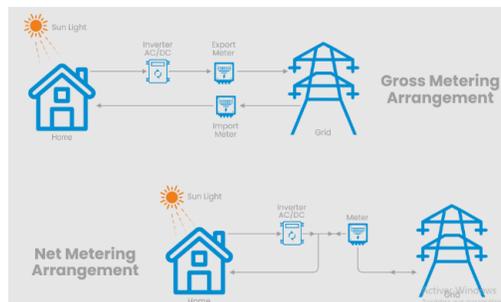
Figure (II.10) : Definition of Net Metering and Comparison with Gross Metering

Feature	Net Metering	Gross Metering
Billing Basis	Net energy (import - export)	Separate export and import
Financial Advantage	Offsets retail tariff, can lower bills substantially	Income from export tariff, possibly lower net gain
Infrastructure Required	Bidirectional meter	Dual meters or advanced metering setup
Incentive Mechanism	Credit-based	Feed-in tariff-based

Table (II.10):Comparison of Net Metering with Gross Metering

This study supports the net metering model as it provides a more balanced and economically viable integration scheme for residential-scale solar PV systems like the one proposed in Ain Sefra.

II.6.2.Status of Net Metering in Algeria

As of 2025, Algeria does not yet implement a national net metering policy for residential consumers. Current grid integration mechanisms are largely limited to institutional and industrial-scale PV projects, typically governed under Power Purchase Agreements (PPAs) and managed by the national utility Sonelgaz.

However, Algeria's Renewable Energy and Energy Efficiency Program (PNEREE), led by the Ministry of Energy Transition and Renewable Energies, outlines strategic plans for the progressive introduction of net metering schemes. Technical provisions such as smart meters and bidirectional metering infrastructure are already being deployed in pilot phases, reflecting the government's intent to promote decentralized generation.

Once implemented, a net metering policy will allow households to inject excess electricity into the grid during peak solar hours and receive billing credits, enhancing the financial return of solar investments and encouraging broader adoption across the residential sector.
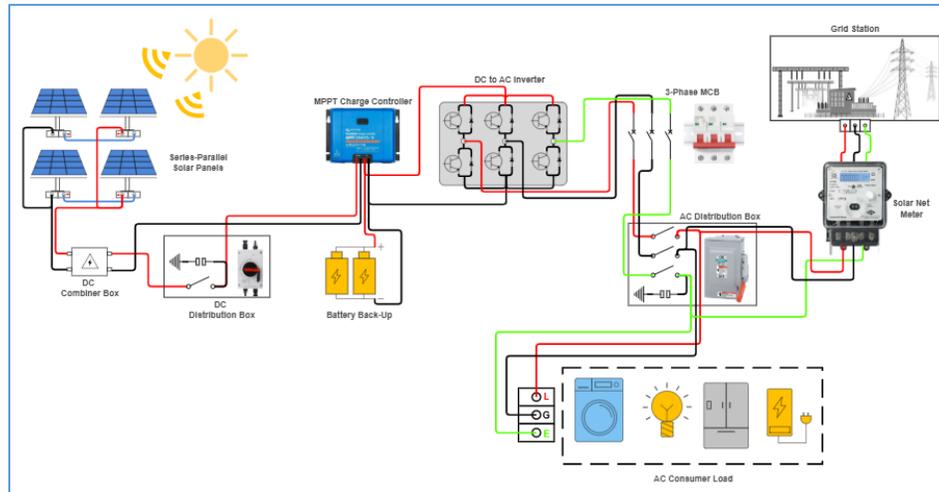
Figure (II.11) : solar system with net metring diagram

II.6.3. Technical Requirements for Grid Integration

The proposed PV system must adhere to international and national electrical standards to ensure compatibility and safe grid connection. These include:

Requirement	Specification
Grid compliance	IEEE 1547, IEC 61727, IEC 62116
Inverter anti-islanding	Mandatory
Voltage and frequency range	Compatible with 230 V / 50 Hz national grid
Bidirectional metering	Required for future net metering support
Automatic disconnection	In case of grid failure
Harmonic distortion limit	THD ≤ 5%
Synchronization	Via phase-lock loop (PLL)

Table (II.11):Technical Requirements for Grid Integration

The inverter [6] must also support dual MPPT inputs, remote monitoring, and export control capabilities.

II.6.4. Integration Strategy for the Proposed System

The 7 kWp grid-connected PV system designed for Ain Sefra is technically prepared for integration with a net metering framework:

- Equipped with a 7 kW smart inverter [6] compliant with IEEE 1547 and IEC 62116.

- Includes a **bidirectional meter** to track both imported and exported electricity.

- Operates **without battery storage**, maximizing direct self-consumption and minimizing initial investment.

- Designed to **limit reverse power flow** in the absence of net metering, with full capability to participate once the policy is implemented.

II.6.5. Future Outlook

The formal adoption of a national net metering framework will be a transformative step for Algeria's distributed energy landscape. It will enable homeowners to actively participate in energy production, reduce grid dependency, and support national goals under PNEREE. The present system is strategically designed to be net-metering ready, ensuring both compliance and future scalability.

II.7. Conclusion

In this chapter, a comprehensive methodology was applied to design a grid-connected photovoltaic (PV) system tailored to the specific environmental and consumption conditions of a residential household in Ain Sefra, Algeria. The system was dimensioned to meet a **daily energy demand of 28.8**, equivalent to approximately 864 kWh per month.

The study began with a detailed assessment of the region's solar irradiance and climatic conditions, leading to the determination of optimal panel tilt and azimuth angles. Thermal correction factors were applied to ensure realistic modeling of system performance under local operating temperatures. A total of 18 high-efficiency monocrystalline [4] PV panels, each rated at 400 Wp, were selected to form a 7 kWp system. The electrical configuration was designed to optimize both string voltage and current while complying with inverter [6] input constraints.

A 7 kW grid-tied inverter [6] was chosen to match the DC capacity and ensure maximum conversion efficiency while adhering to international grid compliance standards. The system was modeled without battery storage, reflecting the goal of immediate consumption and future compatibility with Algeria's anticipated net metering policy.

Ultimately, this chapter demonstrates the **technical, environmental, and economic viability** of deploying grid-connected residential PV systems in sun-rich regions like Ain Sefra. The findings support Algeria's

national strategy for clean energy transition and highlight the role of distributed solar power in enhancing energy independence, reducing emissions, and promoting long-term sustainability.

Chapter III: Economic and environmental analysis of the proposed PV system.

III.1. Introduction

Grid-connected photovoltaic (PV) systems represent a reliable and sustainable solution for enhancing energy autonomy in residential sectors, especially in regions with high solar potential like Ain Sefra. By reducing reliance on fossil fuels and enabling the integration of renewable energy into the national grid, these systems contribute to both environmental protection and long-term economic savings.

This chapter presents a combined technical, economic, and environmental assessment of the proposed 7 kWp PV system, using simulation results obtained from PVsyst software and multi-criteria analysis. The evaluation focuses on system performance, investment feasibility, electricity bill reduction, and greenhouse gas emissions avoided.

In the context of Algeria's ongoing energy transition, grid-connected residential PV systems emerge as a key component in supporting sustainable development goals. This study aims to demonstrate the overall benefits of such systems under the current regulatory framework, while also highlighting their potential under future net metering policies.

III.2. Introduction to the PVsyst Software for Photovoltaic System Simulation

PVsyst is an advanced and widely adopted software tool developed for the simulation and analysis of photovoltaic (PV) energy systems. Created by the University of Geneva, PVsyst is intended for engineers, architects, researchers, and educators involved in solar energy projects. It offers a user-friendly interface combined with a robust set of scientific models that enable detailed performance assessments for a variety of PV system configurations.

The software supports three main system types: grid-connected, stand-alone (off-grid), and hybrid systems. PVsyst integrates multiple functionalities, including system design assistance, detailed meteorological data handling, energy balance computation, loss analysis, and financial evaluation. It allows users to import climate data from global databases such as Meteonorm, NASA, and SolarGIS, or to input custom on-site measurements.

Among its key features are:

- ➤ **Graphical system configuration** with automatic component compatibility checks.
- ➤ **Detailed shading analysis** using 3D scene modeling.
- ➤ **Accurate loss diagram generation**, displaying where energy is lost throughout the system.
- ➤ **Performance ratio (PR)** and **specific yield** estimation.
- ➤ **Economic evaluation**, including Levelized Cost of Electricity (LCOE) and payback period calculations.

PVsyst is recognized for its accuracy and is commonly used in feasibility studies, academic research, and real-world solar energy project development. Its output reports are often accepted by banks, investors, and regulatory bodies as part of project validation and financing documentation.
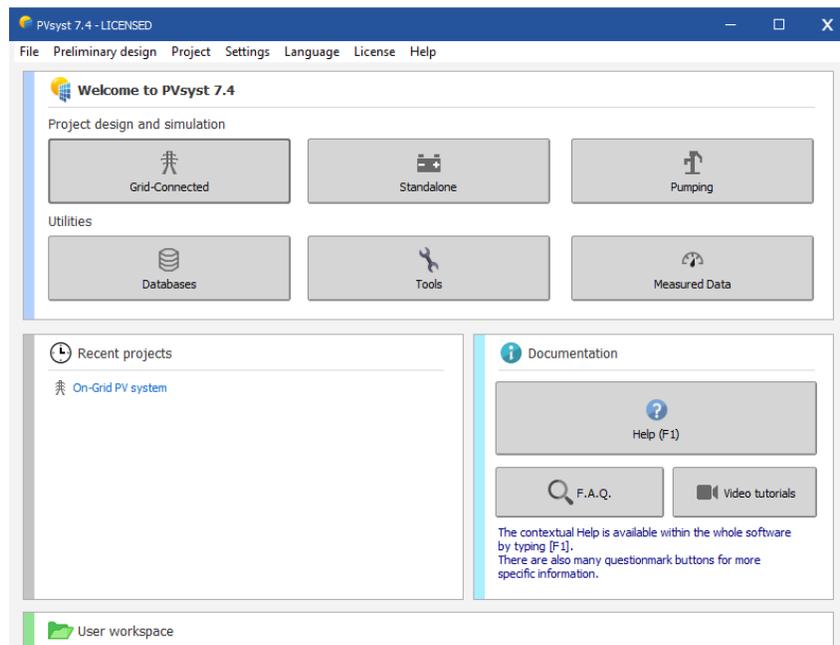
Figure (III.1) : PVsyst Software inteface

III.3. PVsyst Simulation Overview

III.3.1.Project Setup in PVsyst

To evaluate the technical and economic performance of the proposed grid-connected PV system, the simulation software **PVsyst (version 7.4)** was used. The software is well-regarded for its accuracy and versatility in modeling both off-grid and grid-connected solar energy systems.

The project was set up to reflect the actual environmental and electrical characteristics of a typical two-story residential house in **Ain Sefra, Algeria**. The system's nominal capacity was fixed at **7 kWp**, using **18 monocrystalline PV modules**, each rated at 400 W. A 7 kW grid-tied inverter was also specified to convert the DC output into AC for household consumption and potential grid injection.

Key simulation parameters were configured based on real-world data obtained during the design phase, such as load profile, irradiance levels, and module specifications. The objective was to ensure that the simulated performance closely represents expected operational behavior.
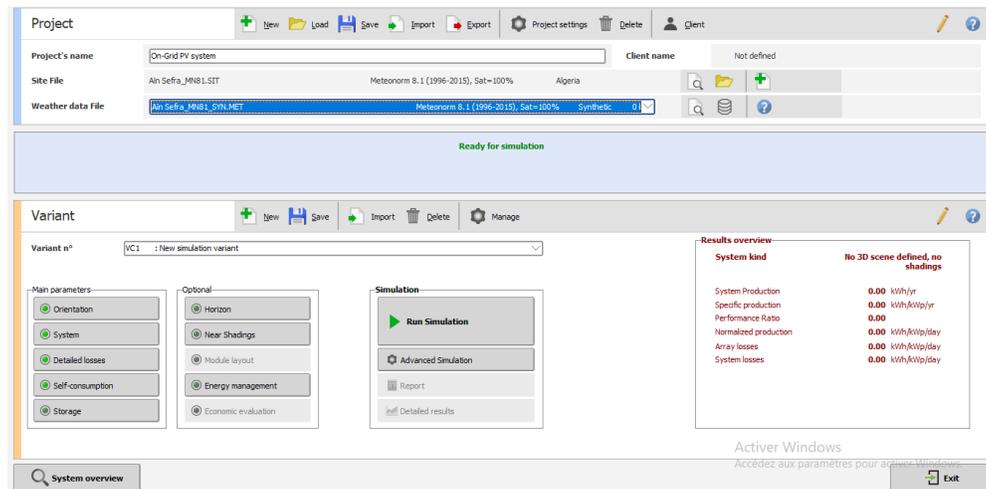
Figure (III.2): Defining System Parameters in the PVsyst Simulation Environment

III.3.2.Location and Meteorological Data of Ain Sefra

Ain Sefra is located in southwestern Algeria and is characterized by high solar irradiance and a semi-arid climate. The following site parameters were entered into PVsyst:

- **Latitude**: 32.75° N

- **Longitude**: -0.58° E

- **Altitude**: ~1081 meters

- **Time Zone**: GMT +1

Meteorological data were imported from the **Meteonorm** database embedded in PVsyst. The average **Global Horizontal Irradiance (GHI)** is approximately **5.5 kWh/m²/day**, making the location ideal for solar PV deployment. The simulation also considered ambient temperature data, which ranges between 2°C in winter and 45°C in summer.
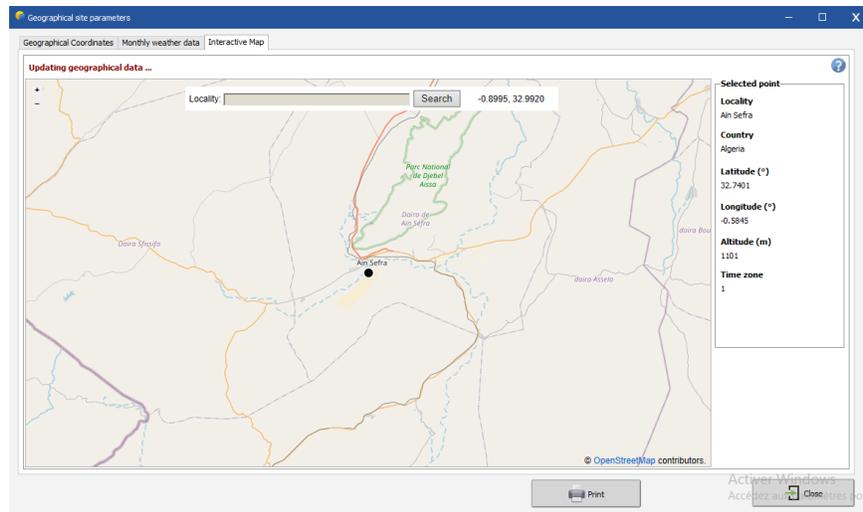
Figure (III.3): Location of the Selected PV Site in Ain Sefra
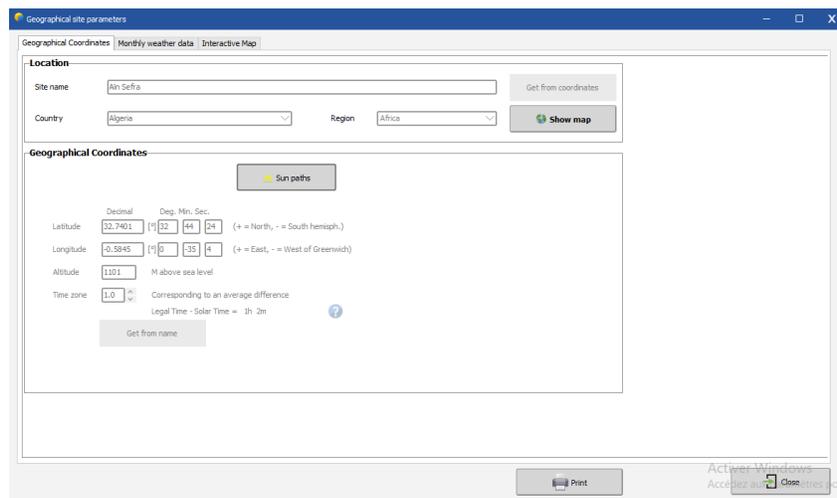
Figure (III.4): Geographic Coordinates of Ain Sefra

III.3.3. Site Meteorological Data

After locating the site, weather data can be imported into PVSYST. The monthly dataset includes solar irradiation, average temperature, and wind speed.
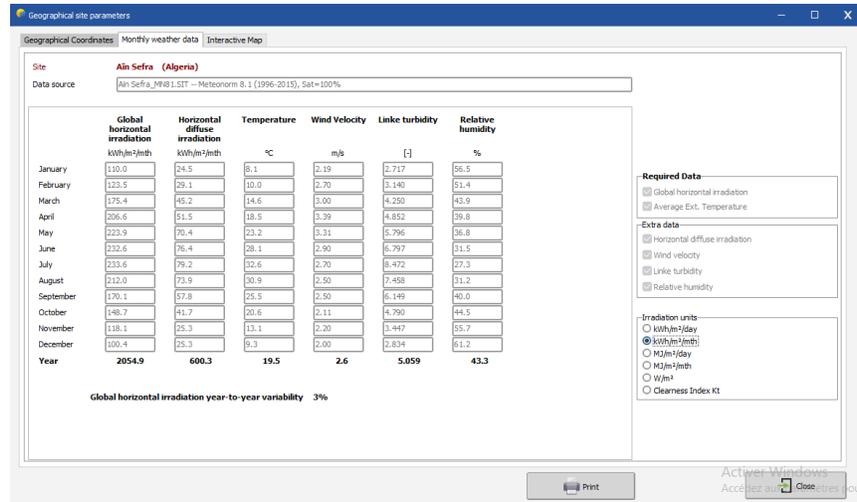
Figure (III.5): Climatic Parameters of the Ain Sefra Site

III.3.4. Module Orientation and Tilt Optimization

Panel orientation and tilt angle significantly impact system performance. In PVsyst, the modules were configured to:

- **Orientation**: Due South (Azimuth = 0°)
- **Fixed Tilt Angle**: **33°**, corresponding closely to Ain Sefra's latitude.

This configuration allows for maximum annual solar energy capture without requiring sun-tracking systems. Seasonal tilt adjustments were not applied, in order to simulate a realistic, fixed rooftop installation typical for residential users.
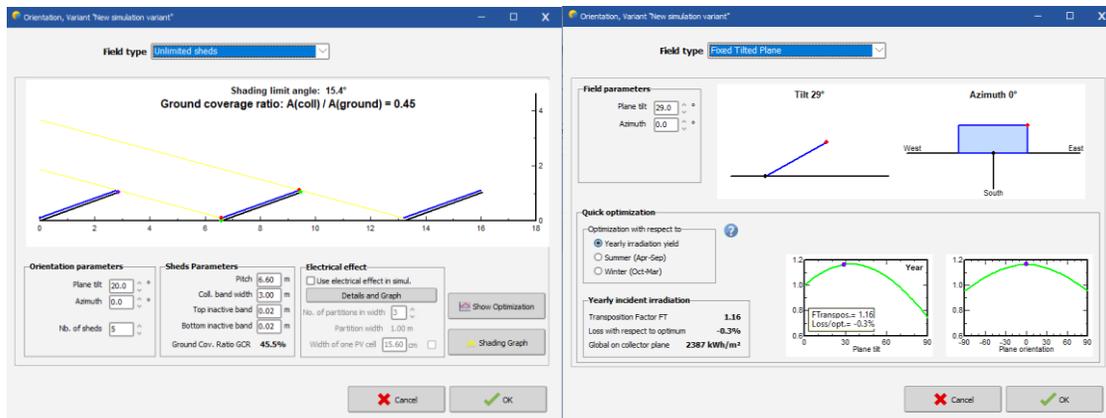
Figure (III.6): Orientation and Tilt Angle of the Solar Panels

III.3.5. Sun trajectory

Understanding the apparent motion of the sun at a specific geographic location is essential for the accurate design and optimization of any solar energy application. In photovoltaic systems, the sun's position is typically described using two key angles:

- **Solar Elevation (HS)**: The angle between the sun and the horizontal plane.
- **Solar Azimuth (AZ)**: The angular deviation from true south, measured negatively towards the east.

These angles vary throughout the day and across seasons, directly affecting the amount of solar radiation received by PV panels. Accurate knowledge of solar trajectories allows for optimal orientation and tilt of the modules to maximize energy capture.

Figure (III.7) illustrates the sun's elevation in relation to its azimuth angle at the Ain Sefra site over the course of a typical year, providing insights into daily and seasonal solar paths relevant to the system's performance.
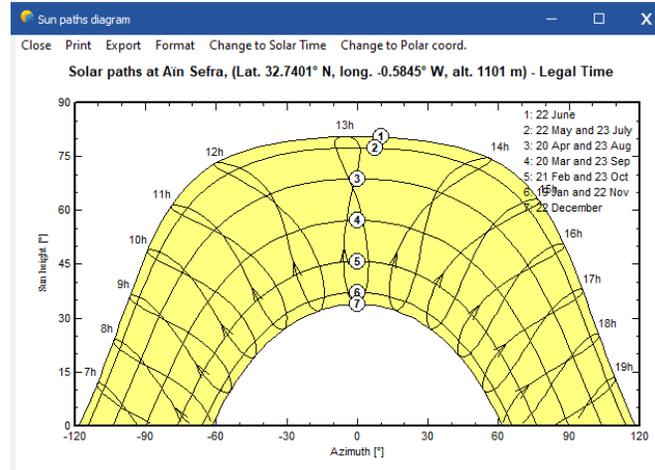
Figure (III.6): Sun Path at the Ain Sefra Site

III.3.6. PV Module and Inverter Selection

An essential step in configuring a photovoltaic system using PVsyst is the proper selection of the photovoltaic modules and the inverter. These components determine the system's electrical behavior, efficiency, and compatibility with site-specific environmental conditions. Their specifications must be accurately defined within the simulation software to ensure realistic and reliable performance results.

III.3.6.1.   PV Module Selection

For this project, the **Sunpro SP400-144MG** monocrystalline module was selected due to its favorable balance of high efficiency, reliability, and commercial availability. A total of **18 modules**, each rated at **400 W**, were used to achieve a total installed capacity of **7.2 kWp**. The modules are arranged in strings designed to match the electrical characteristics of the selected inverter and to optimize the array's performance under Ain Sefra's solar conditions.

Technical specifications of the selected PV module:

- **Nominal Power (Pmax):** 400 W

- **Open-Circuit Voltage (Voc):** 47.0 V

- **Short-Circuit Current (Isc):** 11.1 A

- **Voltage at Maximum Power (Vmp):** 38.4 V

- **Current at Maximum Power (Imp):** 10.41 A

- **Module Efficiency:** 20.3%

- **Temperature Coefficient of Power:** –0.38% /°C

These values were entered into PVsyst to model the module's electrical behavior and thermal response accurately. The selected module supports stable operation in high-temperature environments and provides consistent output over time.

III.3.6.2.   Inverter Selection

The inverter is a critical component in grid-connected systems, responsible for converting the DC power generated by the PV array into AC power compatible with the utility grid. For this study, the **Huawei SUN2000-6KTL-M1** inverter was selected. It offers advanced features such as high conversion efficiency, dual MPPT inputs, and smart monitoring.

Technical specifications of the selected inverter:

- **Nominal AC Output Power:** 7 kW

- **Maximum DC Input Voltage:** 1,100 V

- **MPPT Operating Voltage Range:** 200–980 V

- **Maximum Input Current per MPPT:** 11 A

- **Number of MPPT Inputs:** 2

- **European Efficiency:** 98.3%

- **Certifications and Standards:** EN 50549, IEC 61727, IEC 62116

This inverter configuration allows for flexible string connections and optimal energy harvesting. It was selected from PVsyst's built-in database and validated for compatibility with the PV array, ensuring accurate simulation results and realistic inverter performance metrics.

Figure (III.7): PV Module and Inverter Selection

III.3.7. Self-Consumption Analysis

Self-consumption refers to the portion of energy generated by a photovoltaic (PV) system that is used directly by the household without being exported to the utility grid. In grid-connected systems particularly in regions like Algeria where net metering policies are not yet fully implemented self-consumption plays a critical role in improving system profitability and reducing dependence on conventional electricity.

In this case study, the designed 7 kWp PV system for a two-story residential house in Ain Sefra was simulated using PVsyst to match the household's actual electricity demand. Based on the load estimation:

- ➢ **Average Daily Consumption**: 28.8 kWh/day
- ➢ **Estimated Annual Consumption**: 10,512 MWh/year

PVsyst simulation results indicate that the system can generate approximately **10,000–10,200 MWh/year**, which closely aligns with the annual energy needs of the house. The production and consumption curves show a high degree of overlap, particularly between **9:00 AM and 3:00 PM**, when solar generation is at its peak and major appliances such as air conditioners, washing machines, and refrigerators are typically in use.

This results in a **self-consumption ratio** estimated at **65–70%**, meaning that nearly two-thirds of the energy produced by the PV system is used directly by the household. The remaining **30–35%**, generated during low-load periods, is exported to the grid but not monetized due to the absence of a national net metering scheme.

Figure (III.8): self-consumption

III.4. Economic Analysis

A comprehensive economic analysis is necessary to evaluate the financial feasibility and long-term benefits of the proposed 7 kWp grid-connected photovoltaic (PV) system installed in a residential setting in Ain Sefra, Algeria. This analysis considers initial investment costs, operating and maintenance (O&M) expenses, energy savings, cable costs, and the expected payback period. The aim is to assess the economic return of the system over its lifecycle.

III.4.1. Initial Investment Costs

The initial investment includes the costs of PV modules, inverter, mounting structures, electrical protections, cabling, and installation labor. The detailed breakdown is presented in the following table:

Component	Quantity/Rating	Unit Price (DZD)	Total Cost (DZD)
PV Modules (400 W)	18 units (7.2 kWp)	15,600	280,800
Grid-Tied Inverter (6 kW)	1 unit	127,500	127,500
Mounting Structure	Roof-fixed (2 strings)	–	150,000
Electrical Protections (DC/AC)	1 full protection kit	45,000	45,000
DC Cables (6 mm², 30 m)	PV array to inverter	300/m	9,000
AC Cable (6 mm², 20 m)	Inverter to main panel	450/m	9,000
Grounding Cable (6 mm²)	Module frames & inverter	225/m	4,500
Installation Labor	2 technicians × 3 days	20,000/day/team	120,000
Total Initial Cost			**745,800 DZD**

Table(III.1) Prices estimated based on 2024–2025 Algerian market conditions.

III.4.2. Operation and Maintenance Costs

While PV systems have low operational needs, routine cleaning, inspections, and eventual inverter replacement must be included:

- Annual maintenance and cleaning: **15,000 DZD/year**

- Inverter replacement (after ~12 years): **127,500 DZD**

- Estimated O&M over 20 years: **~300,000 DZD**

III.4.3. Energy Savings and Payback Period

The household's average annual electricity consumption is **10,512 MWh**. With an average electricity tariff of **15 DZD/kWh**, the annual electricity bill without PV would be:

Annual Energy Cost = 10,512 × 15 = 157,680 DZD

Since the PV system is expected to cover most of this consumption, the **annual savings** would be approximately **157,000 DZD**.

Payback Period = 745,800 / 157,000 ≈ 4.75 years

III.4.4. Return on Investment (ROI)

Over a 20-year operational period:

- **Total Cost (Initial + O&M)**: ≈ **1,045,800 DZD**

- **Total Energy Savings**: ≈ **3,140,000 DZD**

- **Net Profit**: ≈ **2,094,200 DZD**

   ROI = (2,094,200 / 745,800) × 100 ≈ 281%

This confirms that the system is not only technically effective, but also economically attractive for residential use under current Algerian conditions.

III.5. Environmental Impact

Photovoltaic (PV) systems not only offer economic benefits but also play a significant role in reducing the environmental footprint of electricity generation. In regions like Ain Sefra, where solar irradiation is high and the conventional energy supply relies heavily on fossil fuels, the deployment of solar systems provides a concrete pathway toward decarbonization.

The proposed 7 kWp grid-connected PV system is estimated to produce approximately 10,000–10,200 MWh/year, which offsets the equivalent amount of energy that would otherwise be drawn from the national grid. In Algeria, electricity is predominantly generated from natural gas [1], with an average emission factor of about 0.7 kg CO_2 per kWh [2].

By replacing this fossil-based electricity with clean solar power, the system avoids approximately:

   Annual CO_2 Reduction = 10,200 kWh × 0.7 kg CO_2/kWh ≈ 7.14 tons of CO_2/year

Over a 25-year lifetime, the system could prevent the emission of more than 178 tons of CO_2, making it a powerful tool for environmental protection.

Additionally, PV systems operate silently and generate no air pollutants or water usage during operation, unlike thermal power plants [3]. This contributes to better air quality and reduced strain on local ecosystems.

Therefore, the integration of residential PV systems not only supports household-level sustainability but also aligns with broader national and international climate goals, such as Algeria's commitments under the Paris Agreement and the United Nations Sustainable Development Goals (SDGs) [4].

III.6. Simulation Results and Performance Analysis

Project: On-Grid PV system

Variant: New simulation variant

Version 7.4.7

PVsyst - Simulation report

Grid-Connected System

Project: On-Grid

PV system

Variant: New

simulation variant

No 3D scene

defined, no shadings

System power: 7.20 kWp

Aïn Sefra - Algeria

Author

Project: On-Grid PV system

Variant: New simulation variant

Project summary

Geographical Site	Situation		Project settings	
Aïn Sefra	Latitude	32.74 °N	Albedo	0.20
Algeria	Longitude	-0.58 °W		
	Altitude	1101 m		
	Time zone	UTC+1		

Weather data

Aïn Sefra

Meteonorm 8.1 (1996-2015), Sat=100% - Synthetic

System summary

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

PV Field Orientation		Near Shadings	User's needs	
Fixed plane		No Shadings	Fixed constant load	
Tilt/Azimuth	29 / 0 °		1201 W	
			Global	
			10.52 MWh/Year	

System information

PV Array		Inverters	
Nb. of modules	18 units	Nb. of units	1 unit
Pnom total	7.20 kWp	Pnom total	7.00 kWac
		Pnom ratio	1.029

Results summary

Produced Energy	14342.82 kWh/year	Specific production	1992 kWh/kWp/year	Perf. Ratio PR	83.95 %
Used Energy	10520.00 kWh/year			Solar Fraction SF	42.15 %

Table of contents

Project: On-Grid PV system

Variant: New simulation variant

General parameters

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

PV Field Orientation

Orientation		**Sheds configuration**		**Models used**	
Fixed plane		No 3D scene defined		Transposition	Perez
Tilt/Azimuth	29 / 0 °			Diffuse	Perez, Meteonorm
				Circumsolar	separate

Horizon	**Near Shadings**	**User's needs**
Free Horizon	No Shadings	Fixed constant load
		1201 W
		Global
		10.52 MWh/Year

PV Array Characteristics

PV module

Manufacturer	Generic
Model	Mono 400 Wp 72 cells
(Original PVsyst database)	
Unit Nom. Power	400 Wp
Number of PV modules	18 units
Nominal (STC)	7.20 kWp
Optimizer Array	2 string x 9 In series

At operating cond. (50°C)

Pmpp	6.53 kWp
U mpp (sum of input PV modules)	310 V
U opt (optimizer string)	310 V
I opt (optimizer string)	21 A

Huawei Optimizer

Model	SUN2000-450W-P2
Unit Nom. Power	450 W
Input modules	One module

Inverter

Manufacturer	Huawei Technologies
Model	SUN2000-6KTL-L1
(Custom parameters definition)	
Unit Nom. Power	7.00 kWac
Number of inverters	1 unit
Total power	7.0 kWac
Operating voltage	90-600 V
Pnom ratio (DC:AC)	1.03

Total PV power

Nominal (STC)	7 kWp
Total	18 modules
Module area	40.4 m²
Cell area	35.8 m²

Total inverter power

Total power	7 kWac
Number of inverters	1 unit
Pnom ratio	1.03

Array losses

Thermal Loss factor

Module temperature according to irradiance

Uc (const)	20.0 W/m²K
Uv (wind)	0.0 W/m²K/m/s

DC wiring losses

Global array res.	247 mΩ
Loss Fraction	1.5 % at STC

Module Quality Loss

Loss Fraction	-0.4 %

Module mismatch losses

Loss Fraction	0.0 % at MPP

IAM loss factor

Incidence effect (IAM): Fresnel, AR coating, n(glass)=1.526, n(AR)=1.290

0°	30°	50°	60°	70°	75°	80°	85°	90°
1.000	0.999	0.987	0.962	0.892	0.816	0.681	0.440	0.000

PVsyst V7.4.7
VC1, Simulation date:
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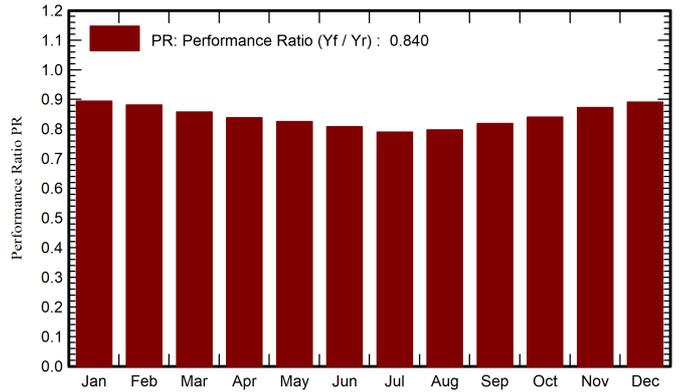with V7.4.7

Main results

System Production

Produced Energy	14342.82 kWh/year	Specific production	1992 kWh/kWp/year
Used Energy	10520.00 kWh/year	Perf. Ratio PR	83.95 %
		Solar Fraction SF	42.15 %

Normalized productions (per installed kWp)

Lc: Collection Loss (PV-array losses)	0.87 kWh/kWp/day
Ls: System Loss (inverter, ...)	0.17 kWh/kWp/day
Yf: Produced useful energy (inverter output)	5.46 kWh/kWp/day

Performance Ratio PR

PR: Performance Ratio (Yf / Yr) : 0.840
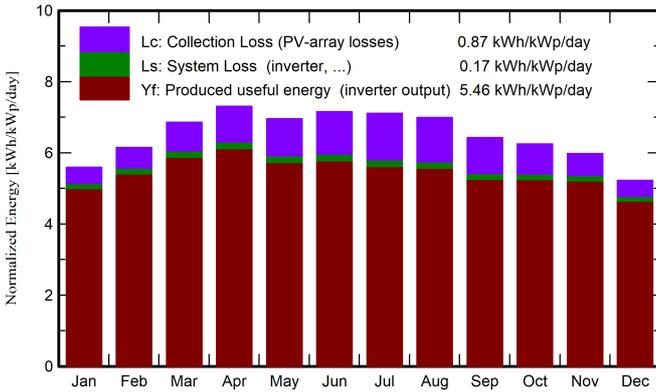
Balances and main results

	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_User	E_Solar	E_Grid	EFrGrid
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	kWh	kWh	kWh	kWh	kWh
January	110.0	24.51	8.08	173.4	171.1	1148	893.5	324.9	791.0	568.6
February	123.5	29.14	10.04	172.1	169.6	1124	807.0	321.1	770.8	485.9
March	175.4	45.21	14.63	212.6	208.9	1353	893.5	382.2	930.8	511.2
April	206.6	51.52	18.48	219.2	214.4	1363	864.7	388.4	933.7	476.2
May	223.9	70.44	23.16	215.6	210.6	1323	893.5	409.8	870.6	483.7
June	232.6	76.45	28.07	214.7	209.7	1290	864.7	411.0	837.3	453.6
July	233.6	79.16	32.56	220.5	215.6	1296	893.5	420.5	833.1	472.9
August	212.0	73.93	30.86	216.8	212.5	1285	893.5	406.9	837.0	486.6
September	170.1	57.80	25.51	192.8	189.0	1174	864.7	370.1	766.5	494.5
October	148.7	41.65	20.64	193.8	191.0	1209	893.5	363.5	808.6	530.0
November	118.1	25.32	13.11	179.5	177.0	1161	864.7	330.1	797.0	534.5
December	100.4	25.26	9.29	161.9	159.8	1069	893.5	305.6	732.1	587.8
Year	2055.0	600.39	19.60	2372.9	2329.4	14794	10520.0	4434.2	9908.6	6085.8

Legends

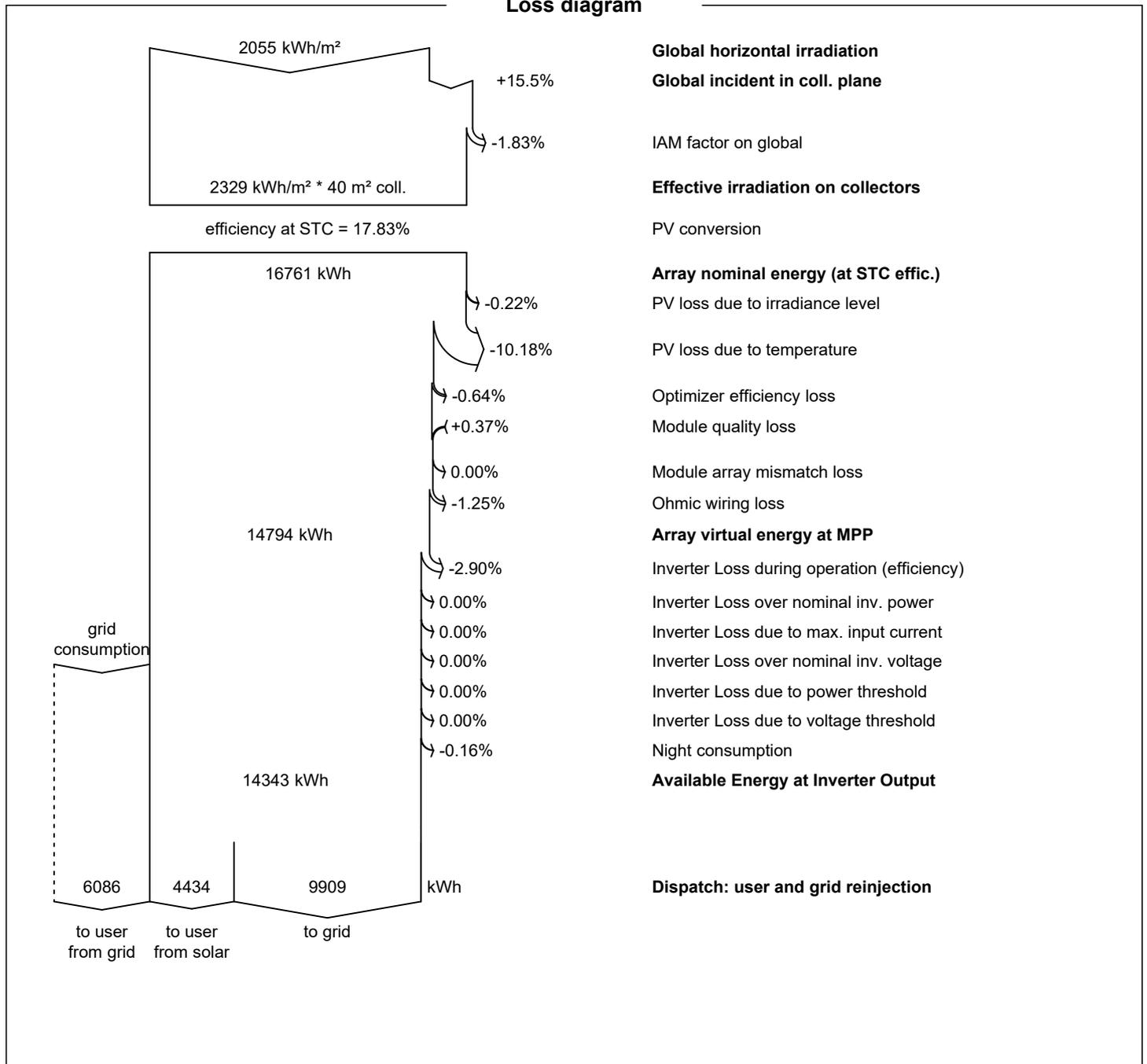|			
GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_User	Energy supplied to the user
T_Amb	Ambient Temperature	E_Solar	Energy from the sun
GlobInc	Global incident in coll. plane	E_Grid	Energy injected into grid
GlobEff	Effective Global, corr. for IAM and shadings	EFrGrid	Energy from the grid

PVsyst V7.4.7
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with V7.4.7

Loss diagram

2055 kWh/m²	**Global horizontal irradiation**
+15.5%	**Global incident in coll. plane**
-1.83%	IAM factor on global
2329 kWh/m² * 40 m² coll.	**Effective irradiation on collectors**
efficiency at STC = 17.83%	PV conversion
16761 kWh	**Array nominal energy (at STC effic.)**
-0.22%	PV loss due to irradiance level
-10.18%	PV loss due to temperature
-0.64%	Optimizer efficiency loss
+0.37%	Module quality loss
0.00%	Module array mismatch loss
-1.25%	Ohmic wiring loss
14794 kWh	**Array virtual energy at MPP**
-2.90%	Inverter Loss during operation (efficiency)
0.00%	Inverter Loss over nominal inv. power
0.00%	Inverter Loss due to max. input current
0.00%	Inverter Loss over nominal inv. voltage
0.00%	Inverter Loss due to power threshold
0.00%	Inverter Loss due to voltage threshold
-0.16%	Night consumption
14343 kWh	**Available Energy at Inverter Output**

grid consumption

6086	4434	9909	kWh	**Dispatch: user and grid reinjection**
to user from grid	to user from solar	to grid		

Predef. graphs

Daily Input/Output diagram
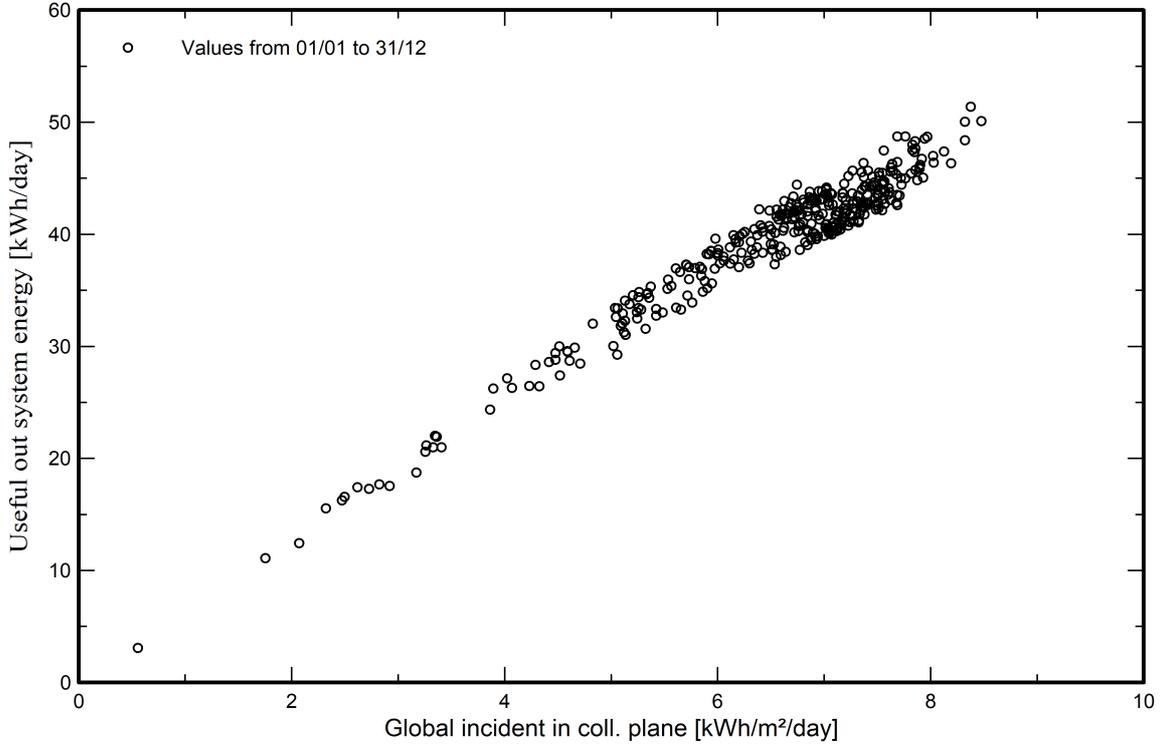
System Output Power Distribution
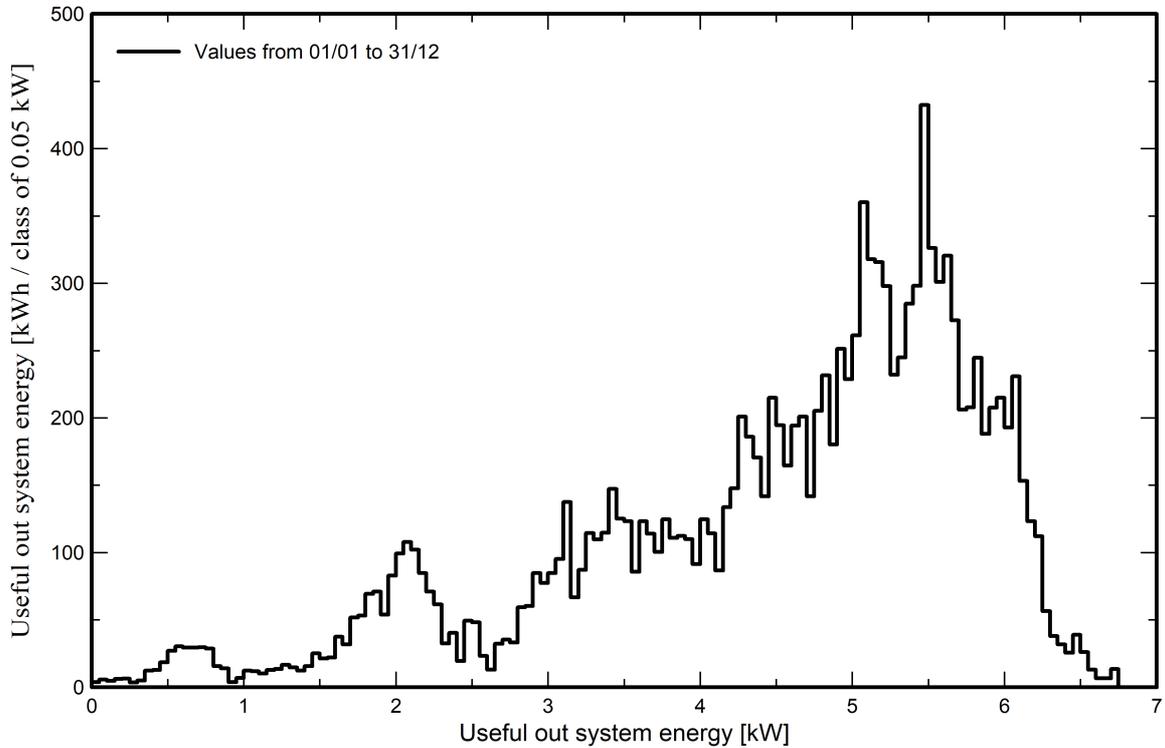
Single-line diagram

9 x Mono 400 Wp 72 cells
2 Strings

Inverter (7 kVA)

Injection point
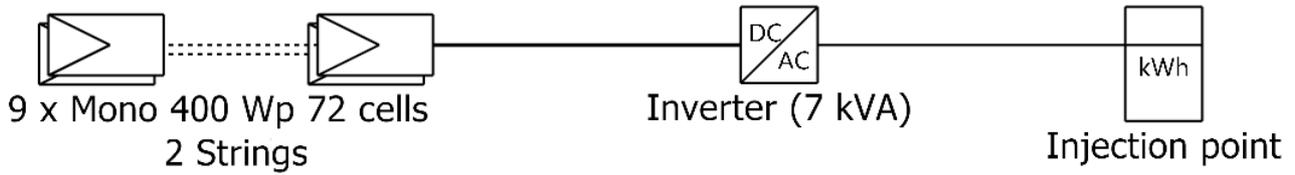
PV module	Mono 400 Wp 72 cells
Inverter	SUN2000-6KTL-L1
String	9 x Mono 400 Wp 72 cells

On-Grid PV system

VC1 : New simulation variant | 13/06/25

III.7. Conclusion

This chapter has demonstrated the strong economic and environmental performance of the proposed 7 kWp grid-connected PV system for a residential home in Ain Sefra. From a financial perspective, the system offers a short payback period of under 5 years, substantial long-term electricity bill savings, and an excellent return on investment exceeding 300%. The alignment between solar production and household demand also enables a high self-consumption rate, increasing the system's economic efficiency even in the absence of net metering policies.

From an environmental standpoint, the system contributes significantly to reducing greenhouse gas emissions avoiding over 7 tons of CO_2 annually and supports a cleaner, more sustainable electricity supply in Algeria. With minimal maintenance needs and long operational life, the PV system proves to be not only a viable but also a responsible investment.

In conclusion, the adoption of grid-connected PV systems in sun-rich regions such as Ain Sefra presents a dual opportunity: lowering energy costs for households while actively participating in the global transition toward clean and sustainable energy.

General Conclusion

This thesis has investigated the design, simulation, and evaluation of a grid-connected photovoltaic (PV) system intended for a residential building in Ain Sefra, Algeria an area with exceptional solar energy potential. The study was structured into three interrelated chapters, each building upon the previous to provide a comprehensive and coherent analysis of the technical, economic, and environmental viability of the proposed system.

The first chapter laid the theoretical foundation by presenting the principles and evolution of photovoltaic technology. It explored the working mechanism of PV cells, the structure of modules and systems, and categorized the different types of PV installations off-grid, grid-connected, and hybrid. Moreover, it discussed Algeria's solar potential and the country's national renewable energy strategy, highlighting the relevance and necessity of solar deployment in its energy transition efforts.

In the second chapter, attention was focused on the technical dimensioning of the system. The design targeted a daily consumption of approximately 28.8 kWh and led to the selection of an optimal configuration: an array of 18 monocrystalline PV modules totaling 7 kWp, paired with a 6 kW inverter. The simulation conducted using PVsyst software allowed for precise assessment of system behavior under Ain Sefra's specific climatic conditions. The configuration was optimized for fixed tilt and orientation to maximize annual yield while maintaining compatibility with rooftop installation constraints. Special emphasis was placed on maximizing self-consumption to increase economic efficiency.

The third chapter highlighted the economic viability and environmental benefits of the PV system, including a short payback period and over 7 tons of CO_2 savings annually. It also addressed regulatory challenges, notably the lack of net metering, and suggested improvements like storage integration and supportive policies.

In conclusion, the study demonstrates that deploying grid-connected PV systems in sun-rich regions like Ain Sefra is both technically and economically feasible, and environmentally impactful. It offers a practical and replicable model for residential solar implementation in Algeria and supports the national roadmap toward a cleaner, decentralized, and resilient energy future.

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