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Comparative Analysis of a Real Photovoltaic Installation Using PVsyst Simulation Software

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Dedication

With the grace and guidance of Allah

I dedicate this humble work:

To my supervisor, **Dr. Sekhane Houcine**, for his valuable assistance, availability, guidance, and wise advice, which greatly contributed to the completion of this work.

To my beloved wife, for her love, unwavering support, patience, and encouragement throughout my academic journey.

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Finally, to all those who contributed, directly or indirectly, to the completion of this dissertation.

Ahcene.

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CHOUAIB

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General Introduction

General Introduction

Electrical energy has become an essential element for economic, industrial, and social development. The continuous increase in global energy consumption, combined with the progressive depletion of fossil fuel resources and growing environmental concerns related to greenhouse gas emissions, has led to an intensified search for alternative, clean, and sustainable energy solutions. In this context, renewable energy sources are playing an increasingly important role in energy strategies adopted worldwide.

Among the various renewable energy sources, solar photovoltaic (PV) energy stands out due to its abundance, availability, and minimal environmental impact. Through the photovoltaic effect, solar radiation can be directly converted into electrical energy without generating pollution or noise. This technology has experienced rapid growth owing to the decreasing cost of equipment, improvements in conversion efficiency, and the implementation of supportive policies in many countries.

Algeria possesses one of the largest solar energy potentials in the world due to its favorable geographical location and high annual solar irradiation levels. This natural resource offers promising opportunities for the development of photovoltaic systems intended to supply residential, administrative, and industrial facilities. However, the success of a photovoltaic project largely depends on the proper sizing of its various components and the accurate assessment of its energy performance.

Within this framework, the present work focuses on the study, sizing, and performance evaluation of a photovoltaic installation designed to supply an administrative site belonging to the SONELGAZ Distribution Directorate of Mila. The main objective is to determine the optimal characteristics of the photovoltaic system required to meet the site's energy demand while ensuring reliable and efficient operation.

To achieve this objective, a methodology based on theoretical calculations and numerical simulation was adopted. The PVsyst software, recognized as one of the leading tools for the design and simulation of photovoltaic systems, was used to evaluate the performance of the proposed system, analyze energy losses, and verify the consistency of the sizing process.

This thesis is organized into three chapters:

The first chapter presents the fundamentals of photovoltaic systems. It covers concepts related to solar radiation, photovoltaic cells, solar modules, and the various stages involved in the sizing of a photovoltaic installation.

The second chapter is devoted to the design and evaluation tools used for photovoltaic systems. It includes a detailed presentation of the PVsyst software, the input data required for simulations, and the main performance indicators used for result analysis.

Finally, the third chapter focuses on the case study of the photovoltaic installation under consideration. It presents the system sizing procedure, PVsyst simulations, analysis of the obtained results, and a comparison between theoretical calculations, simulation results, and the actual operating data of the studied installation.

The overall objective of this study is to demonstrate the importance of simulation tools in the design of photovoltaic systems and to contribute to the promotion of renewable energy integration within administrative and industrial infrastructures.

Chapter I : Fundamentals of Photovoltaic Systems and Their Sizing

I.1. Introduction

Photovoltaic solar energy results from the direct conversion of a portion of solar radiation into electrical energy. This transformation is achieved through a photovoltaic (PV) cell, which operates based on a physical phenomenon known as the "photovoltaic effect."

This chapter presents a state-of-the-art review of the various studies and work concerning solar panels, which form the basis of our research. We will begin by presenting essential concepts related to photovoltaic systems. Subsequently, we will address the operating principle of a photovoltaic cell as the main component of a solar panel, enabling the production of the electrical energy required for the application under study.

I.2. Solar energy and solar radiation

Solar energy is a renewable energy source derived from the radiation emitted by the Sun. It is produced in the form of electromagnetic waves covering a broad spectrum, ranging from ultraviolet rays to infrared rays. Thanks to nuclear reactions occurring within its core, the Sun continuously releases a considerable amount of energy into space.

Despite the vast distance between the Earth and the Sun, estimated at approximately 150 million kilometers, our planet receives a significant portion of this radiation. The amount of solar energy reaching the Earth's surface is extremely high, making this resource a promising solution for meeting current and future energy needs while preserving the environment. Figure I-1 presents a close-up view of the Sun's outer structure **[SB]**.

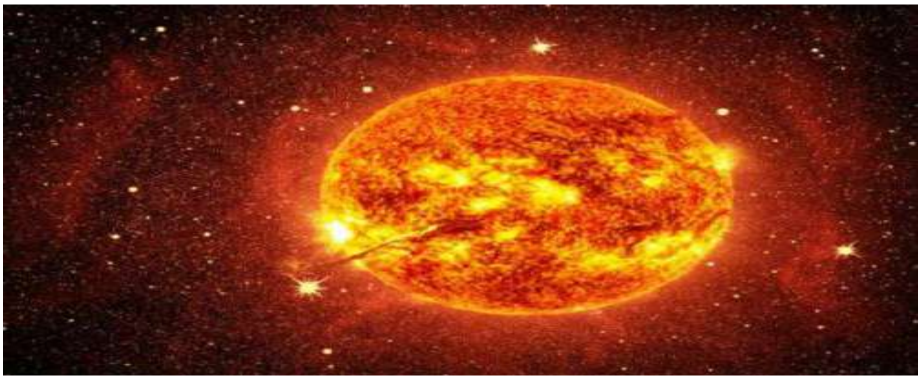


Figure I-1: Exterior structure of the Sun.

I.2.1. Solar radiation

The Sun emits electromagnetic radiation covering a wide range of wavelengths, between 0.22 µm and 10 µm. The energy associated with this radiation is distributed approximately as follows: 9% in the ultraviolet range, 47% in the visible range, and 44% in the infrared range.

The average solar power density received by the Earth's atmosphere is approximately 1.37 kW/m^2, with a variation of about ±3% due to changes in the distance between the Earth and the Sun during its orbit. A portion of this energy is absorbed by the atmosphere, which generally limits the power reaching the Earth's surface to a value below 1200 W/m^2.

Furthermore, the Earth's rotation and the tilt of its axis influence the amount of solar energy received depending on latitude, time of day, and season. In addition, meteorological conditions—such as clouds, fog, or suspended atmospheric particles—cause variations in solar radiation, which can be categorized as either direct or diffuse.

- **Direct radiation** is the component of solar radiation that reaches the Earth's surface without being scattered by the atmosphere.
- **Diffuse radiation** refers to the portion of solar radiation scattered in all directions by air molecules and particles present in the atmosphere. This scattering phenomenon depends essentially on the size and nature of the particles encountered.
- **Reflected radiation**, also known as ground albedo, represents the fraction of solar radiation reflected by the Earth's surface. This reflection can be specular (when it occurs in a specific direction) or diffuse. In general, the ground reflects radiation in a diffuse and non-uniform manner.
- **Global radiation** refers to the total solar radiation received on a horizontal surface at ground level. It is equal to the sum of the diffuse radiation and the direct radiation component projected onto a horizontal surface (corrected by the cosine of the Sun's zenith angle), as illustrated in Figure I-2 **[SF]**.

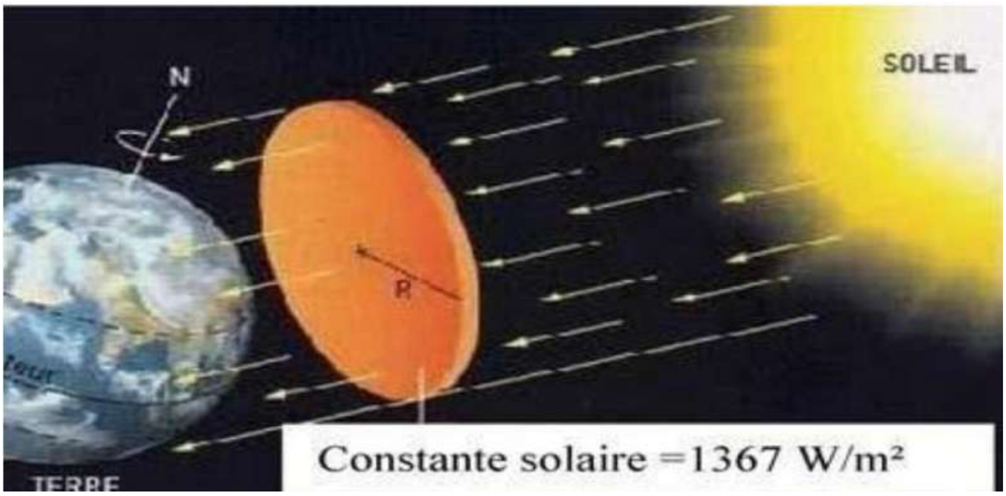


Figure I-2: Types of solar radiation received at the earth's surface.

I.2.2. Radiation spectrum

Electromagnetic radiation consists of waves that travel at the speed of light in a vacuum, denoted as $c \approx 3\times108$ m/s. These waves can be characterized by their wavelength (λ) or their frequency (ν), which are linked by the relationship $c = \lambda \times \nu$. One can also use the wavenumber, defined as the inverse of the wavelength ($\sigma = 1 / \lambda$).

The solar spectrum, shown in Figure I-3, indicates that visible radiation occupies a narrow band, with wavelengths ranging between 0.38 µm and 0.78 µm. Shorter wavelengths belong to ultraviolet radiation, followed by X-rays and gamma rays. Wavelengths greater than those of the visible range correspond to infrared radiation, followed by microwaves **[MMHA]**.

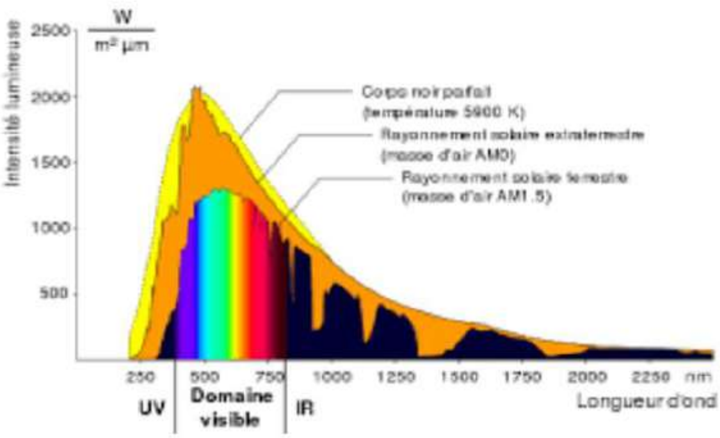


Figure I-3: Spectral distribution of solar radiation

I.2.3. Solar irradiation

Irradiation is the amount of solar energy received by a unit surface area over a specified period, typically expressed in Wh/m² or kWh/m² (Figure I-4).

Global irradiation represents the total sum of this energy. It combines three main components:

- **Direct irradiation:** Solar rays that reach the surface directly without being altered.
- **Diffuse irradiation:** Solar rays scattered by the atmosphere (clouds, dust, etc.).
- **Reflected irradiation:** Radiation reflected by the ground or surrounding surfaces.
- **Global Irradiation:** The total irradiation received on a surface, combining all components:

  Global Irradiation = Direct Irradiation + Diffuse Irradiation + Reflected Irradiation.

  In PV systems, global irradiation is the primary data used to estimate the energy that solar panels can produce **[Site PVsist]**.

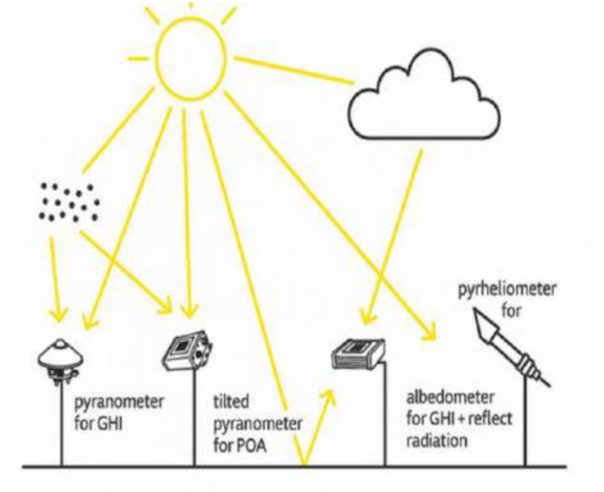


Figure I-4: Distribution of solar irradiation in PV systems.

I.2.4. Factors influencing photovoltaic production

The main factors affecting photovoltaic power production are the following:

- **Temperature:** High temperatures generally reduce panel efficiency, while lower temperatures can increase it. Thin-film cells are less sensitive to heat than crystalline silicon cells. Therefore, the choice of panel type must take the local climate into account.
- **Light Intensity:** Panels perform optimally under direct sunlight. Low light intensity limits electricity production. Solar tracking devices can improve efficiency by optimizing exposure.

- **Shading:** Obstacles such as trees or buildings reduce the amount of light received by the cells and can create "hotspots," which may damage the panels. A well-chosen location and, if necessary, the use of bypass diodes can mitigate this effect.
- **Climatic conditions:** Climatic conditions play a significant role in panel performance. Efficiency is maximized when solar rays strike the surface perpendicularly. The angle of incidence, cloud cover, and atmospheric conditions influence the amount of energy captured.
- **Lifespan and maintenance:** The performance of solar panels decreases gradually over time due to the aging of the semiconductor materials. The accumulation of dust and debris on the surface also reduces efficiency. Regular maintenance is therefore necessary to preserve performance. Despite this gradual degradation, solar panels generally have a lifespan of 20 to 25 years **[sitePVsyst]**.

I.3. Photovoltaic cell

The photovoltaic cell (or photocell) is the basic element of photovoltaic modules (Figure I-5). A solar panel consists of several cells connected in series, in parallel, or in a series-parallel combination to achieve the voltage and current suitable for the intended application, whether domestic or industrial.

Figure I-5: Photovoltaic solar module.

Each PV cell is manufactured from semiconductor materials and directly converts sunlight into electrical energy. Its size generally ranges from a few square centimeters to approximately 100 cm², and its shape can be square, circular, or derived from these geometries. The solar cells can be interconnected in two configurations:

- **Series connection:** The electrons generated by one cell are transmitted to the next, which allows for the addition of voltages while maintaining the same intensity (current). This enables achieving specific nominal voltages (e.g., from 6 V to 24 V) while keeping the current constant.
- **Parallel connection:** The cells are connected such that the total voltage remains identical to that of a single cell, while the total current increases in proportion to the number of connected cells **[ABURV]**.

As shown in Figure I-6 below, the equivalent electrical circuit model of a single-diode photovoltaic cell incorporates a current source to model the incident light flux (I_{ph}), a diode to account for the polarization phenomena of the p–n junction, and two resistors: a series resistor (R_s) through which the current (I) flows, and a parallel or "shunt" resistor (R_{sh}) through which the current (I_{sh}) flows, in order to model the energy losses within the cell **[SFUS]**.

According to Kirchhoff's current law, the output current of the photovoltaic cell can be expressed as:

$$\overrightarrow{I_{cell}} = \vec{I} = \overrightarrow{I_{Ph}} - \overrightarrow{I_d} - \overrightarrow{I_{sh}} \quad \text{(I. 1)}$$

where (I_d) is the diode current.

In cases where the shunt resistance (R_{sh}) is much higher than the series resistance (R_s), the current I_{sh} can be neglected; therefore, equation (I.2) simplifies to:

$$\overrightarrow{I_{cell}} \approx \vec{I} = \overrightarrow{I_{Ph}} - \overrightarrow{I_d} \quad \text{(I. 2)}$$

The operation of a photovoltaic cell is based on the physical phenomenon known as the "photovoltaic effect," which consists of establishing an electromotive force when a cell is exposed to light **[BFDD]**.

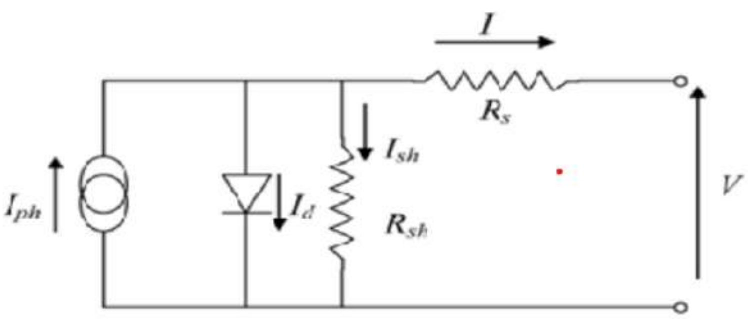


Figure I-6: Electrical equivalent circuit of a single-diode photovoltaic cell.

I.3.1. Operating principle

Under illumination, electron-hole pairs photogenerated in the space charge region (SCR) are instantly separated by the electric field present therein (Figure I.7). The holes, which are positively charged, are accelerated toward the P-region, while the electrons, which are negatively charged, are accelerated toward the N-region. These carriers then become majority carriers: this is the generation photocurrent.

In parallel, minority carriers—holes generated on the N-side and electrons generated on the P-side—create a concentration gradient and diffuse through the material. If they reach the SCR without recombining, the electric field causes them to cross the depletion zone to reach the region where they become majority carriers: this is the diffusion photocurrent.

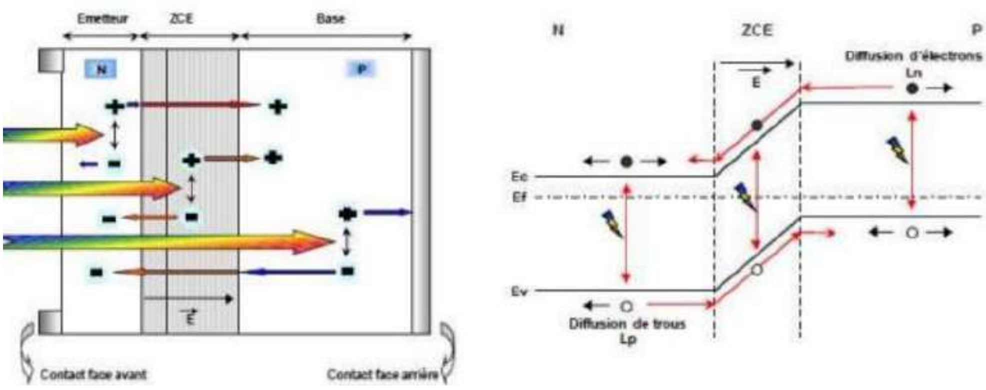


Figure I-7: Structure and energy band diagram of a photovoltaic cell under illumination.

I.3.2. I–V and P–V characteristics

The current-voltage (I–V) characteristic represents the variation of the current delivered by a photovoltaic cell as a function of the voltage across its terminals. It allows for the identification of the cell's key electrical parameters, such as the short-circuit current (I_{sc}), the open-circuit voltage (V_{oc}), and the maximum power point (MPP). This characteristic depends on solar irradiance and temperature conditions.

The power-voltage (P–V) characteristic describes the evolution of the power produced by the photovoltaic cell as a function of voltage. Power is obtained by the product of voltage and current ($P = V \times I$).

The P–V curve exhibits an optimal operating point known as the "maximum power point" (MPP), which corresponds to the maximum power the cell can deliver under given conditions.

These two characteristics are essential for analyzing the performance of photovoltaic cells and optimizing the operation of solar systems, as presented in Figure I-8 **[SQINSA]**.

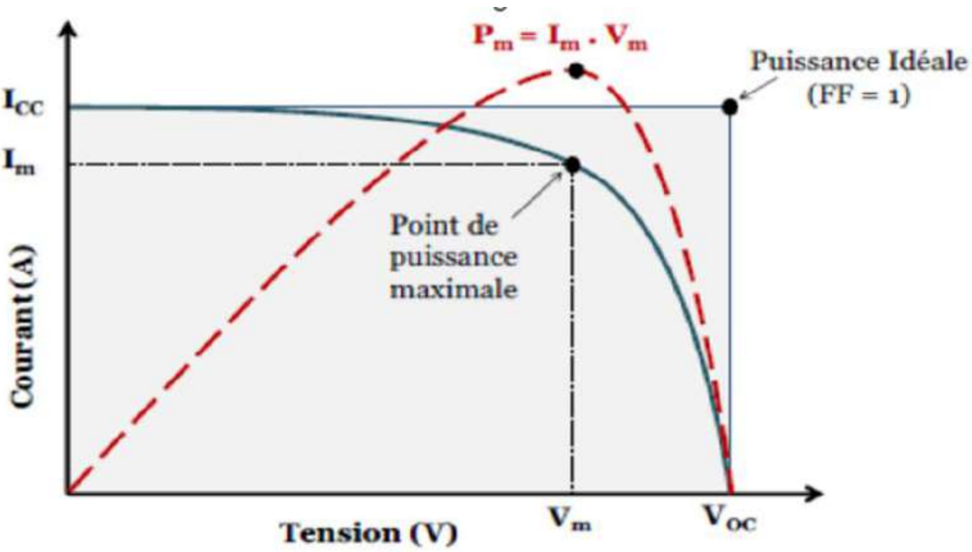


Figure I-8: Electrical characteristics (I–V and P–V) of a solar cell.

I.3.3. Principal electrical parameters of photovoltaic cells and modules

- **Open-circuit voltage (V_{oc}):** The open-circuit voltage is the voltage generated by a solar panel when it is not connected to any load. It is a fundamental parameter that indicates the maximum voltage of a solar panel. It depends on the cell technology, the received irradiance, and the temperature. The higher the Voc value, the higher the potential voltage of the panel.
- **Short-circuit current (I_{sc}):** The short-circuit current is the current flowing through a solar panel when its terminals are short-circuited. It indicates the maximum current production capacity of a panel for a given irradiance. The higher the Isc value, the higher the current generated by the panel.
- **Voltage at maximum power point (Vmp or Vmpp):** This is the voltage delivered by a solar panel when it operates at its maximum output power. It indicates the optimal voltage level for operating the panel under specific sunlight and temperature conditions.
- **Current at maximum power point (Imp or Impp):** This is the current generated by the solar panel at the maximum power point. This parameter indicates the optimal current that the panel can deliver.

- **Efficiency (η):** Efficiency is the ratio between the maximum electrical power produced by a solar panel (Pmpp) and the incident solar energy received on its surface. The higher this value, the better the panel's ability to convert sunlight into electricity.

  The maximum power (Pmpp) is the product of the voltage and current at this optimal operating point:

  Pmpp = Vmpp × Impp

  The efficiency (η, %) is calculated by dividing the maximum power output (P_{mpp}) by the product of the panel surface area (A, m²) and the solar irradiance (G), under standard test conditions (1000 W/m²), as given in Equation (I.3) **[JINGSUN]**:

$$\eta = \frac{Pmpp}{Surface \times 1000} \times 100 \qquad (I.3)$$

I.4. Photovoltaic modules and generators

Connecting several photovoltaic cells in series or in parallel forms a photovoltaic generator. If the cells are connected in series, the voltages of each cell are added together, increasing the total generator voltage. Conversely, if the cells are connected in parallel, the current intensity increases, as illustrated in the following figures.

I.4.1. Series/parallel connection

- **Series connection of PV cells:** The individual cell, the basic unit of a photovoltaic system, produces only a very small amount of electrical power, typically around 0.5 W with a voltage of less than one volt. To increase the available power, cells are assembled to form a module (or panel). Connecting cells in series delivers a voltage equal to the sum of the individual voltages, while the total current is equal to that of a single cell. Figure I-9 illustrates how photovoltaic panels are connected in series.

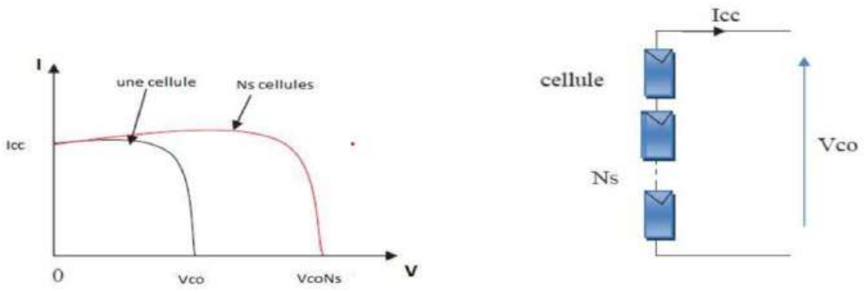


Figure I-9: Series connection of photovoltaic panels.

- **Parallel Connection of PV Cells:** By connecting identical modules in parallel, the generator's voltage remains equal to the voltage of each individual module, while the total current increases proportionally to the number of modules connected in parallel. Figure I-10 presents the parallel configuration of photovoltaic panels **[LAUMMTO]**.

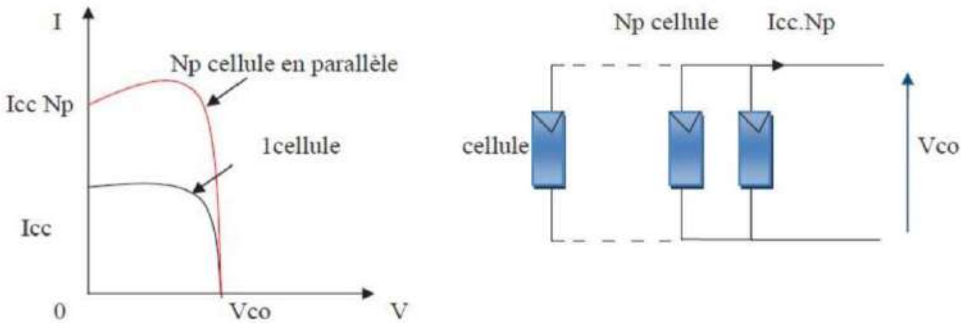


Figure I-10: Parallel connection of photovoltaic panels.

I.4.2. Temperature influence

The influence of temperature on the I=f(V) and P=f(V) characteristics at constant irradiance. We maintained a constant irradiance (100W/m2) for various temperatures (25°C, 40°C ,50°C, 70°C).

Figure I-11 shows that temperature has a negligible impact on the short-circuit current (I_{sc}). However, the open-circuit voltage (V_{oc}) decreases markedly with increasing temperature, resulting in a reduction in the photovoltaic cell's output power **[RKHRVR]**.

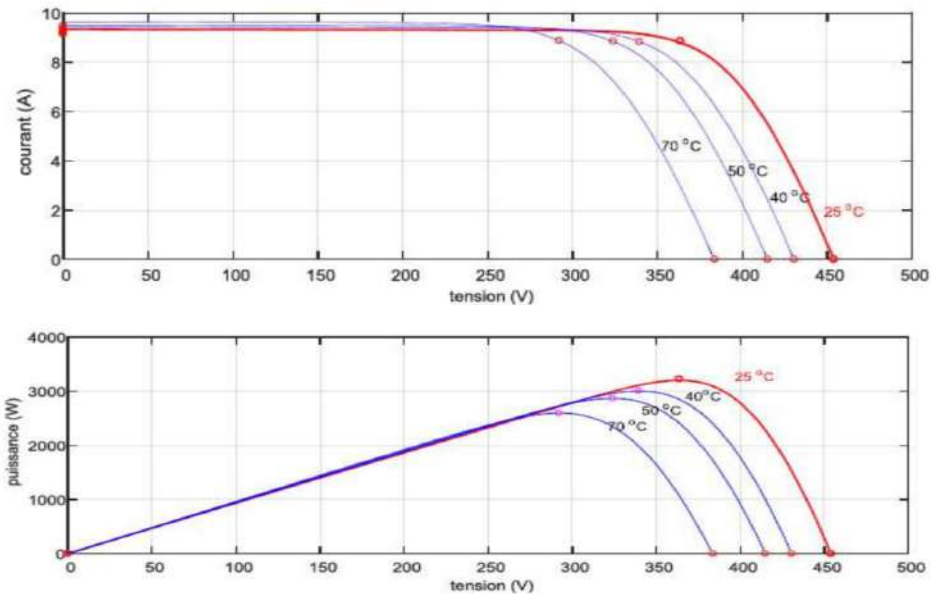


Figure I-11: Effect of temperature on the I–V and P–V characteristics of a PV cell.

I.4.3. Influence of irradiance

Irradiance is the solar radiation power received per unit area, generally expressed in W/m2. It has a direct influence on the performance of photovoltaic systems.

- **Produced current:** The output current is nearly proportional to the irradiance. If the irradiance doubles, the current produced is approximately multiplied by two. Low irradiance leads to a significant decrease in current.
- **Produced voltage:** The voltage varies much less than the current. When irradiance increases, the voltage increases slightly. When irradiance decreases, the voltage drops moderately.
- **Output power:** The electric power produced increases with irradiance. High irradiance allows for power output close to the panel's nominal power. In cloudy weather or in the presence of shading, the power drops sharply **[RMUT]**.

Figure I-12 illustrates the influence of irradiance on the voltage–temperature characteristic (V = f(T)).

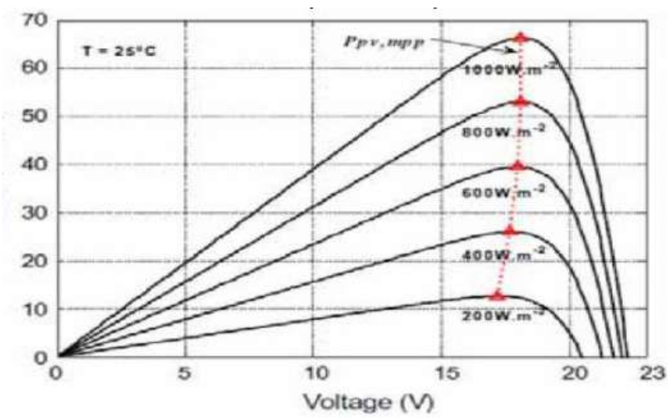


Figure I-12: Voltage–temperature curves under different irradiance levels.

I.5. Components of a photovoltaic installation

The technical details of the main components are structured below:

I.5.1. Photovoltaic modules (panels)

The panels capture sunlight and convert it into direct current (DC).

- **Technology:** Primarily monocrystalline (the most efficient, with an efficiency of 20% to 24%) or polycrystalline.

- **Composition:** They consist of silicon cells connected together and protected by tempered glass.

I.5.2. The inverter

The inverter is the "brain" of the system (Figure I-13).

- **Function:** It converts the direct current (DC) produced by the panels into alternating current (AC), which is the only type of current usable by your appliances or injectable into the grid.
- **Variations:** Central inverters manage all panels in series, whereas micro-inverters manage each panel individually to optimize performance.

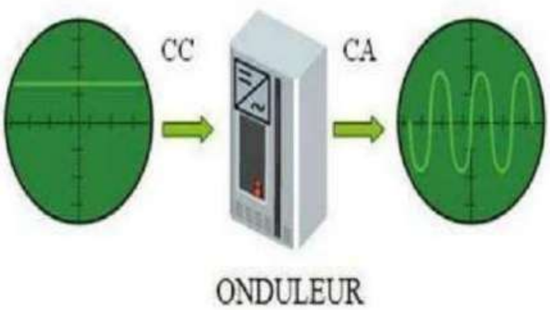


Figure I-13: Role of the inverter in a photovoltaic system.

I.5.3. The storage system (batteries)

Required only for standalone (off-grid) systems or for self-consumption with storage.

- **Role:** They store excess energy produced during the day to be used at night.
- **Associated component:** A charge controller is often included to prevent overcharging or deep discharge of the batteries.

I.5.4. The regulation system

The controller is the heart of the photovoltaic collection system (Figure I-14). It is a small device placed between the photovoltaic panels and the battery to prevent the battery from being damaged by an excessive current or, conversely, from discharging too deeply. Its primary role is to reduce the current when the battery is nearly fully charged. The battery's state of charge is estimated by measuring the voltage across the terminals of the cells. When a battery approaches a full state of charge, small bubbles begin to form on the positive electrodes **[MDCDER]**.

From this point on, it is better to reduce the charging current, not only to avoid damage but also to more effectively reach a full state of charge. Charge regulation aims to limit the battery voltage (high threshold). Furthermore, an excessively high current can even cause deformation of the electrodes inside, which could create a short circuit. For this reason, the installed devices are equipped with charge indicators or a discharge limiter to disconnect the battery as soon as the voltage level drops below a determined threshold.

Figure I-14: Charge controller in a PV system.

I.5.4. Protection box (AC/DC)

A vital safety element, it protects the installation and your home against surges and short circuits.

- **DC Side:** Circuit breakers and surge arresters located between the panels and the inverter.
- **AC Side:** Residual-current device (RCD) and circuit breaker located between the inverter and your electrical panel **[BSUT]**.

I.6. Sizing methodology for a photovoltaic installation

The sizing methodology consists first of determining the peak power of a photovoltaic panel capable of providing the necessary electrical energy during the day. It requires defining the period of electricity needs and the required consumption. This step involves few calculations but requires significant consideration, as an error at this stage can render the photovoltaic installation inadequate **[DMCFES]**.

I.6.1. Consumption estimation

A well-adapted system requires an assessment of the electrical power of the appliances to be powered. The energy required is expressed as:

$$E_c = P \times t \quad \text{(I. 4)}$$

Where:

- E_c: Energy consumed.
- P: Operating power of the appliance.
- t: Usage time.

Energy is therefore the product of power and time. This relationship allows for the calculation of daily energy needs. Since a photovoltaic system must provide energy over an entire day, it is natural to use a 24-hour period as the unit of time. Energy (E) is therefore the electrical energy consumed over 24 hours by the appliance, expressed in Watt-hours per day (Wh/day), also known as daily consumption.

To calculate the total consumption of an installation (E_t), calculate the electrical energy consumed over 24 hours for each piece of equipment and then add them together:

$$E_t = \sum P_i \times t_i \quad \text{(I. 5)}$$

Where:

- P_i: Electrical power of appliance "i" in Watts (W).
- t_i: Usage duration of appliance "i" in hours per day (h/day).

When all devices operate at the same voltage, daily consumption can also be calculated in Ampere-hours per day (Ah/day), a practical unit for battery-linked systems.

Since these devices operate on alternating current and the load is supplied through an inverter, it is necessary to account for the inverter efficiency (η) when evaluating the required power, as shown in Equation (I.6) **[RRAZ]**:

$$P_{\text{corrected}} = \eta_{\text{inverter}} \times P_{\text{appliances}} \quad \text{(I. 6)}$$

Where:

- $P_{appliances}$: total power required by the AC loads.
- $\eta_{inverter}$: inverter efficiency (typically 0.9–0.98).
- $P_{corrected}$: actual power that must be supplied from the DC side (PV/battery side).

I.6.2. Photovoltaic array sizing

Sizing the PV array consists of determining the peak power, the number of solar panels, and their connection method in order to satisfy the installation's energy needs. Table I-1 shows the relationship between field voltage and rated power.

Rated Power (Wc)	Less than 500	From 501 to 2000	From 2001 to 10000	Above 10000
Field Voltage (V)	12	24	48	96

Table I-1: Field voltage versus rated power **[RLUSTHB]**.

I.6.3. Inverter sizing

The power inverter is sized according to several criteria:

- **Input voltage:** This must match the battery or charge controller voltage (12, 24, or 48 V DC).
- **Output voltage:** In Algeria, we use 220/230 V, 50 Hz.
- **Nominal power:** This is the power appliances consume to operate "normally." To determine this value, simply sum the power requirements of all electrical appliances likely to be used simultaneously. Always choose an inverter with a power rating slightly higher than the total power of the appliances.
- **Maximum (peak) power:** The inverter must be able to provide high power (generally 2 or 3 times the nominal power). This feature is necessary for appliances with motors (refrigerators, microwaves, washing machines, etc.) because their consumption increases significantly during start-up. Generally, if the nominal power is sized correctly, the maximum power provided by these inverters is sufficient.
- **Efficiency:** A portion of the processed electricity is consumed by the inverter (typically, between 80% and 95% of the energy is delivered to the output). It is important to check this efficiency, as a high-quality product is usually around 90%. Furthermore, most inverters consume energy even when they are not in use (standby mode). Some are equipped with an on/off system that allows for significant energy savings in small photovoltaic installations.

I.6.4. Storage sizing

To size the battery bank, follow these steps:

a) Calculate the energy consumed (E_c) by the various loads.

b) Determine the required number of days of autonomy (*N*).

c) Determine the acceptable depth of discharge (*D*) for the type of battery used.

d) Calculate the battery capacity (*C*) using the formula below:

$$C = \frac{E_C \times N}{D \times U} \tag{I.7}$$

Where:

- *C*: Battery bank capacity in Ampere-hours (Ah).
- E_c: Energy consumed per day (Wh/day).
- *N*: Autonomy duration (number of days).
- *D*: Maximum allowable discharge (e.g., 0.8 for lead-acid batteries).
- *U*: Battery voltage (V).

The number of batteries in series (N_s) is calculated using the following formula:

$$N_s = \frac{U_t}{U} \tag{I.8}$$

Where: U_t is the total field voltage (V).

The number of batteries connected in parallel (N_p) is determined using the following expression:

$$N_p = \frac{C_t}{C} \tag{I.9}$$

Where: C_t is the total capacity of the battery bank associated with the entire photovoltaic installation (Ah).

Battery lifespan decreases rapidly as the depth of discharge increases. In general, it is recommended to limit the depth of discharge to 50%, meaning only half of the battery capacity is effectively used **[MJTNK]**. Figure I-14 illustrates the general appearance of a Sonic Power solar battery.

Figure I-15: Overview of a solar battery.

I.6.5. Verification of electrical constraints

This involves ensuring that a device, cable, or installation operates without exceeding its permissible electrical limits.

The main constraints to be verified are:

- **Voltage:**
  - Verify that the operating voltage does not exceed the nominal voltage of the equipment.
  - Monitor for potential surges (lightning, switching operations, faults).
- **Current:**
  - Verify that the steady-state current remains below the allowable current capacity of the conductors and devices.
  - Control for potential overloads.
- **Heating:**
  - Calculate Joule effect losses (P_J), using the equation below:

$$P_J = R \times I^2 \quad (I.10)$$

  - Verify that the temperature of the conductors remains within the permissible limits of their insulation.
- **Short-circuit:**
  - Determine the maximum short-circuit current.
  - Verify that cables, circuit breakers, and fuses can withstand the associated thermal and electrodynamic stresses.
- **Voltage drops:**
  - Verify that the voltage drop between the source and the load complies with standards.

    - In low-voltage systems, it is often limited to 3–5% depending on the application.
- **Insulation:**
    - Verify insulation resistance between conductors and earth (ground).
    - Check isolation distances and protection levels.
- **Personnel protection:**
    - Verify the sizing of residual-current devices (RCDs).
    - Control the grounding system and equipotential bonding **[PVsyst]**.

I.7. Conclusion

This chapter presented the fundamental concepts related to photovoltaic systems as well as the main steps for their sizing. After addressing solar energy and the parameters influencing production, the operation of the photovoltaic cell and the electrical characteristics of the modules were studied. The various components of an installation were also presented in order to understand their role in the overall system operation. Finally, the sizing methodology highlighted the essential steps to determine the photovoltaic array power, the choice of inverter, potential storage, and the verification of electrical constraints. These fundamentals constitute an essential element for the design and performance evaluation of a photovoltaic installation.

Chapter II: Design and evaluation tools for photovoltaic systems

II.1. Introduction

The design and assessment of photovoltaic (PV) systems require specialized software tools to size system components, estimate energy production, and analyze the technical and economic performance of an installation. *PVsyst* is among the most widely used software packages and is considered an international benchmark in the field of PV simulation. It enables the sizing of PV arrays, inverters, and storage systems while accounting for local meteorological data, electrical losses, and specific equipment characteristics.

Other tools are also employed in PV studies, such as *PVGIS* (Photovoltaic Geographical Information System), which provides solar irradiation data and energy production estimates based on reliable climatic databases. HOMER Pro is particularly well-suited for the techno-economic analysis of hybrid systems, while *SAM* (System Advisor Model) allows for the evaluation of both energy and financial performance for various PV projects. Using these tools helps improve sizing accuracy, reduce production-related uncertainties, and optimize the overall performance of PV installations.

II.2. Overview of PVsyst software

This subsection is structured around the following key elements:

II.2.1. Definition of PVsyst

PVsyst is a benchmark software widely used for the simulation, design, and analysis of PV systems. The software allows for the assessment of the technical and energy feasibility of PV projects, the optimization of system configurations, and the precise estimation of energy output. It supports various system types, including grid-connected systems, off-grid systems, and solar water pumping systems.

PVsyst integrates numerous advanced features, such as 3D shading analysis, system component sizing, detailed energy loss evaluation, production statistical analysis, and economic project studies. These tools ensure reliable simulations that are representative of real-world operating conditions. Furthermore, the software supports the latest PV technologies, including bifacial modules, single- or dual-axis solar trackers, and battery storage solutions. Thanks to these capabilities, PVsyst remains one of the most widely used tools worldwide for designing and optimizing high-performance, cost-effective PV installations **[ARXHE]**.

II.2.2. Scope of application

PVsyst is software dedicated to pre-sizing studies in the field of photovoltaics. It is used for the design and rigorous sizing of solar energy systems. It allows for the modeling of various installation types, including both grid-connected and off-grid systems. The software offers a comprehensive library of PV cell technologies and batteries, covering products from the wide range of manufacturers available on the market **[MMAHRAB]**.

PVsyst also incorporates multiple factors that influence the performance of PV installations, such as shading losses, electrical losses, temperature effects, module degradation, battery storage management, and potential grid power interruptions. Thanks to these advanced features, it serves as a reliable tool for technical optimization and performance assessment in any photovoltaic project **[Site PVsyst]**.

II.2.3. Main features

PVsyst is a benchmark software for the study, design, and simulation of photovoltaic systems. Its main features include:

- **System design:** PVsyst provides a complete environment for designing PV systems, whether grid-connected, off-grid, or for solar water pumping. Through its sizing tools, the software assists the user in selecting and configuring components, enabling the development of high-performance installations tailored to project requirements.
- **System sizing:** PVsyst provides advanced tools for sizing PV modules and inverters. The software analyzes electrical characteristics through current-voltage (I-V) curves and power distribution, while verifying component compatibility. It facilitates inverter sizing optimization and provides a detailed loss analysis to improve overall performance.
- **Flexible orientations:** PVsyst offers great flexibility in configuring PV arrays by allowing an unlimited number of orientations. It also permits the combination of fixed structures and solar trackers within a single simulation, resulting in more realistic modeling for diverse project configurations.
- **Sub-hourly simulation:** PVsyst allows for the import of meteorological data at sub-hourly time steps (notably via Meteonorm). This functionality enables more accurate simulations by accounting for fine-scale variations in climatic conditions, thereby enhancing the reliability of system behavior assessment.

- **Simulation and results:** PVsyst calculates the annual energy output of the PV system and provides essential indicators such as total energy generated, overall yield, and specific energy. Through detailed reports, the software highlights system gains and losses, facilitating the precise evaluation of overall efficiency and performance **[MMLACHA]**.

II.3. PVsyst simulation input data

Simulating a photovoltaic system using PVsyst requires several categories of input data:

II.3.1. Meteorological data

Meteorological data are fundamental for PV system simulation in PVsyst. The necessary elements include:

- **Geographic coordinates and imports:** Latitude, longitude, altitude, time zone, sun path trajectory, and data imports (Meteonorm, NASA-SSE, PVGIS TMY, etc.) (Figure II-1).
- **Monthly data:** Global horizontal irradiation (GHI), diffuse irradiation, ambient temperature, wind speed, Linke turbidity factor, and relative humidity (Figure II-2).
- **Interactive map:** Geographic visualization of location data (Figure II-3).

Example for Mila (Algeria):

- Latitude: 36.45° N
- Longitude: 6.26° E
- Altitude: approx. 490 m

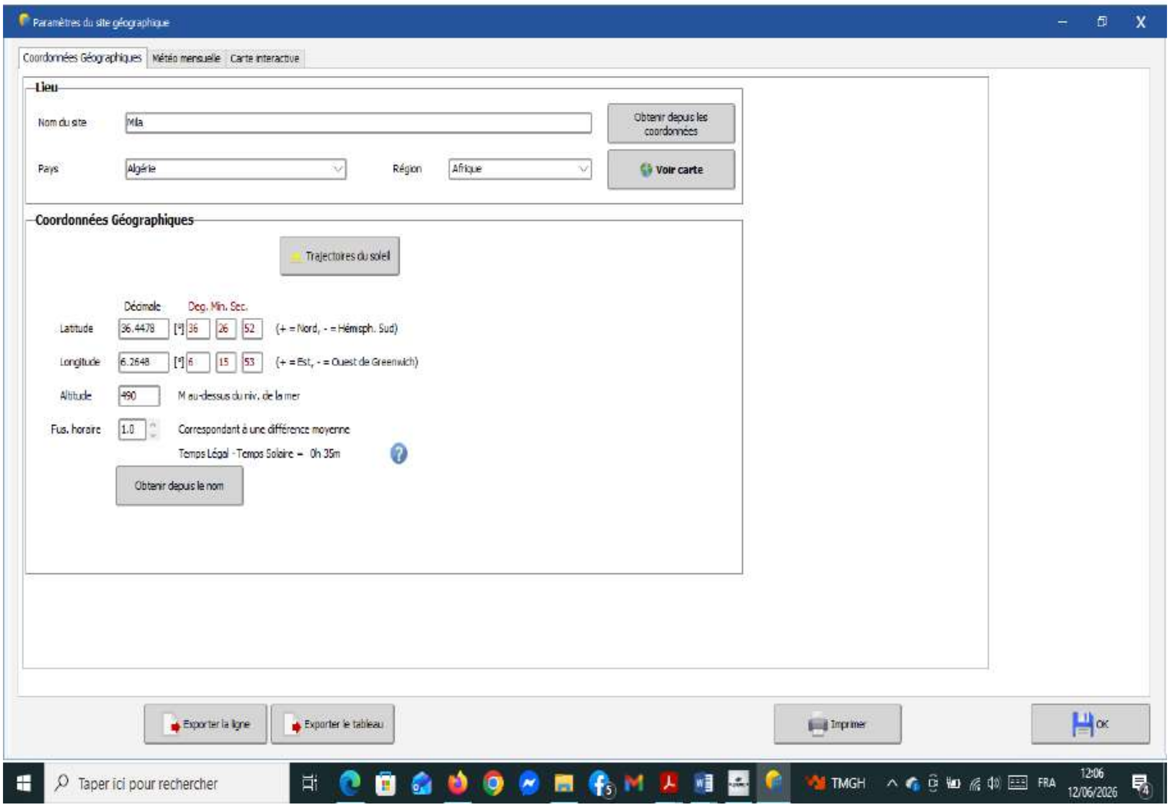


Figure II-1: Geographic coordinates.

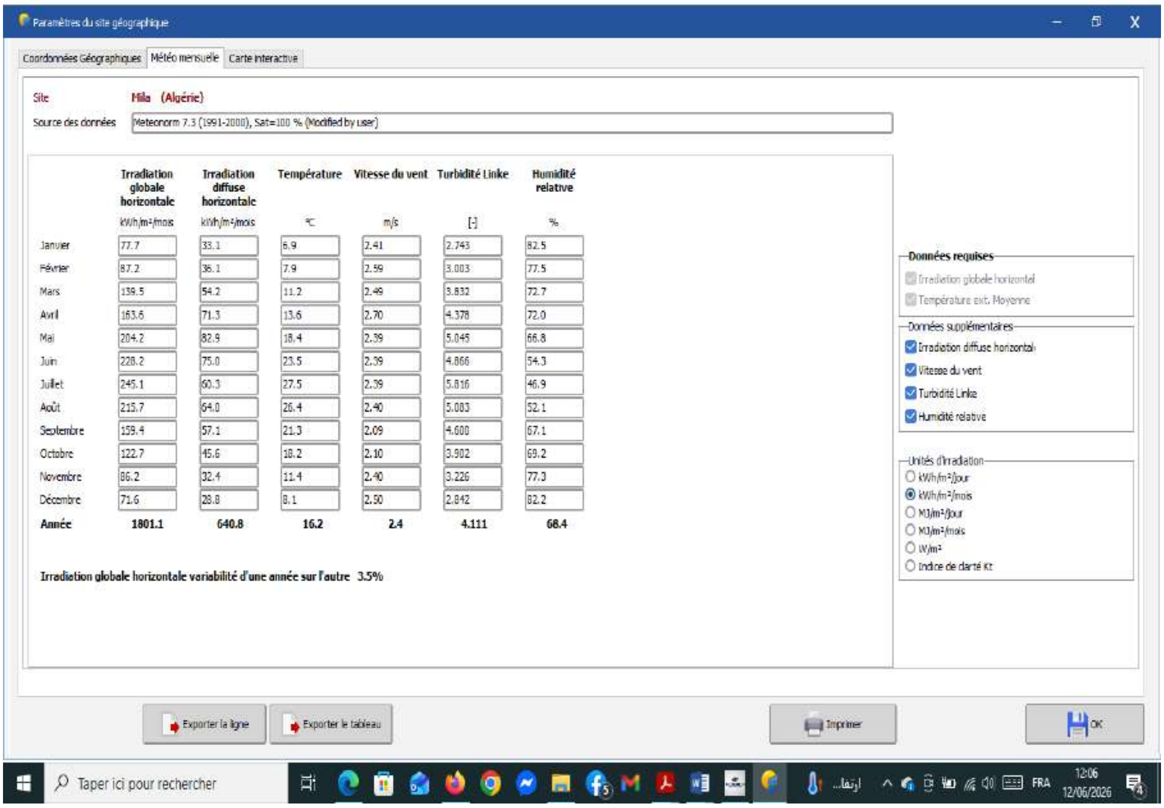


Figure II-2: Monthly meteorological data.

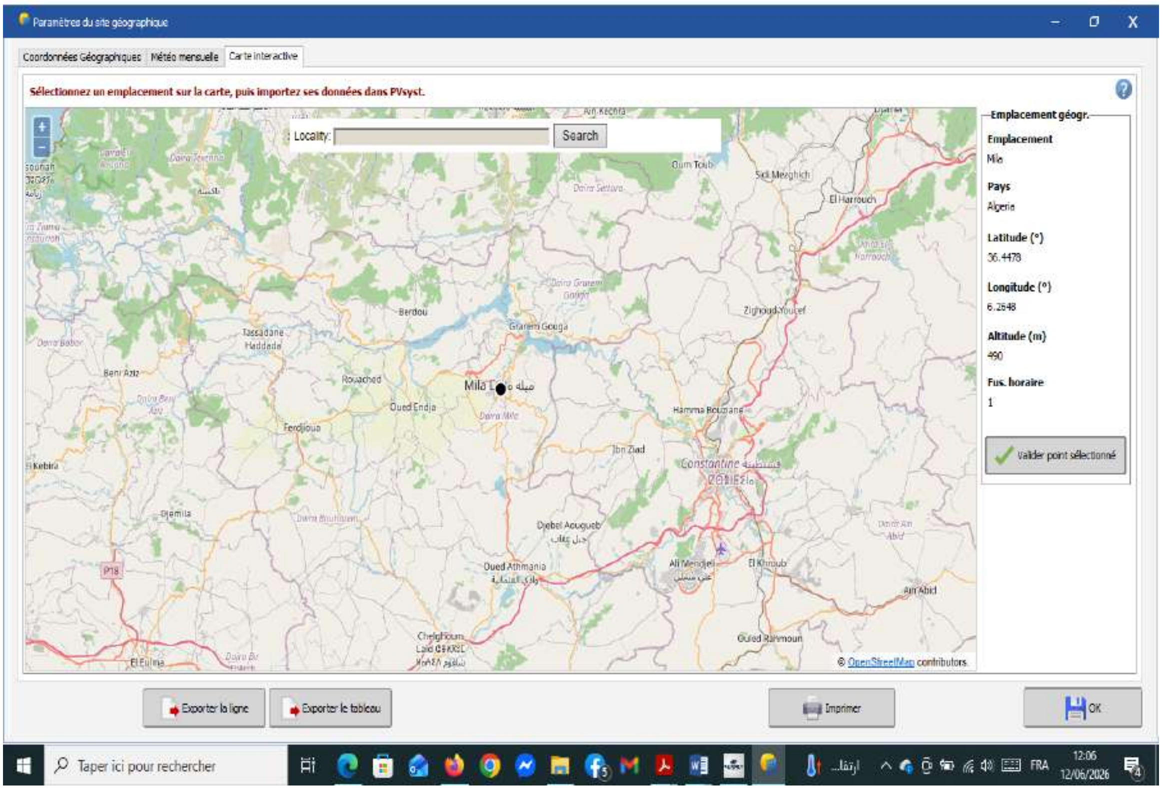


Figure II-3: Interactive map interface.

II.3.2. Selection of photovoltaic modules

Sizing the photovoltaic array is a critical stage in the design of a solar energy system. There is a wide range of PV module technologies available, each with distinct technical specifications and performance characteristics. Consequently, the selection of the PV module must be based on several criteria, as indicated in Figure II-4:

- Manufacturer;
- Panel model;
- Rated power (Pmax);
- Voltage at maximum power point (Vmpp);
- Current at maximum power point (Impp);
- Open-circuit voltage (Voc);
- Short-circuit current (Isc);
- Temperature coefficient.

In particular, the selection process must consider the energy requirements of the installation, the module efficiency, its compatibility with other system components, and its ability to ensure adequate energy production.

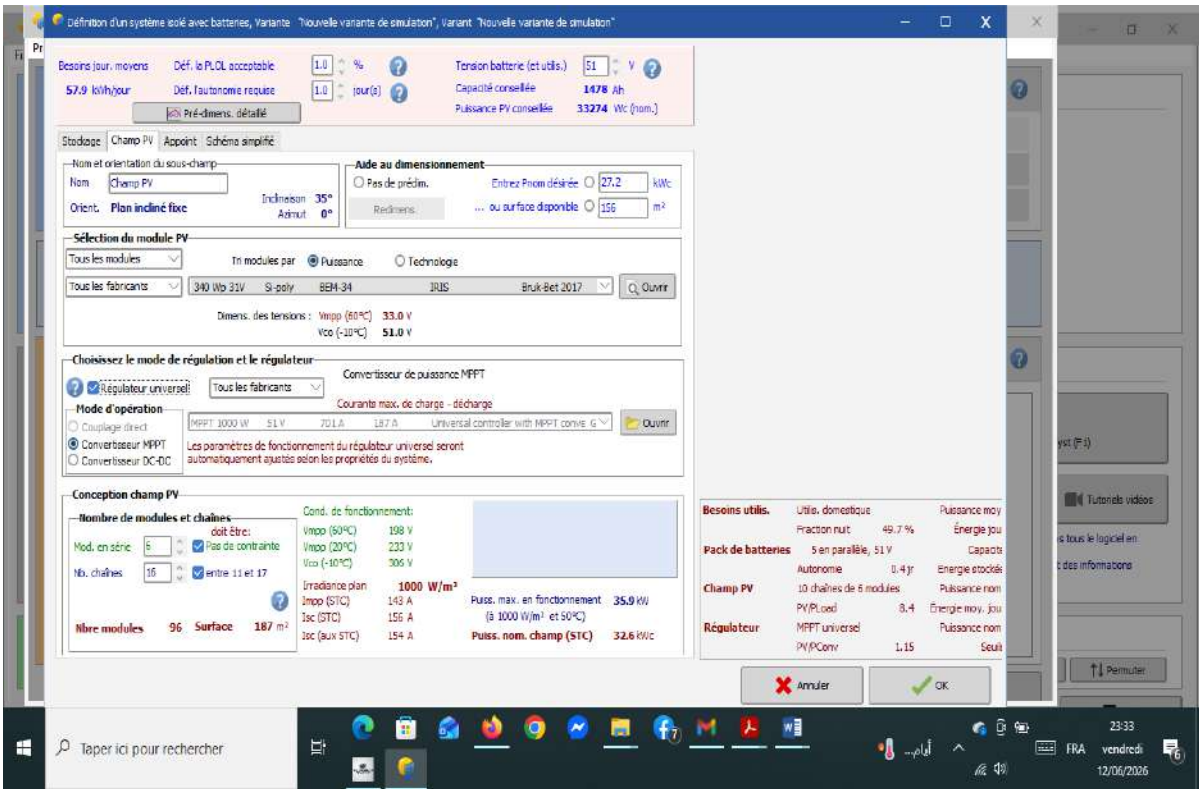


Figure II-4: Selection of the photovoltaic module and inverter.

II.3.3. Inverter selection

The inverter is a critical component of any photovoltaic system, as it converts the direct current (DC) generated by the PV modules into alternating current (AC), compatible with electrical equipment or the utility grid. Its selection must be based on several technical parameters to guarantee the reliability and efficiency of the installation **[MMLACHA]**.

The main selection criteria are as follows:

- **Nominal power (W):** It must be matched to the power of the PV array and the connected load. Proper sizing optimizes inverter operation and improves efficiency.
- **Nominal input voltage (VDC):** It must be compatible with the voltage range provided by the PV array or the storage system, while remaining within the inverter's permissible operating limits.
- **Nominal output voltage (VAC):** This is the effective AC voltage delivered by the inverter to power electrical loads or for grid injection.
- **Operating frequency (Hz):** It must comply with the utility grid frequency (typically 50 Hz).

- **Efficiency:** It represents the ratio between output power and input power. High efficiency minimizes conversion losses and improves overall system performance.

All these parameters must be considered to ensure efficient conversion of the energy produced, as illustrated in Figure II-5.

II.3.4. System configuration

System configuration defines the architecture and arrangement of the installation's components. This step involves determining the number of modules, their connection methods (series/parallel), and their compatibility with the selected inverter.

The main objective is to ensure an optimal match between the PV generator and the inverter while respecting electrical constraints (admissible voltage and current ranges). An appropriate configuration optimizes energy production, limits losses, and ensures safe and reliable system operation.

II.4. Main Parameters and performance indicators

The key performance indicators for a photovoltaic system are energy production, the Performance Ratio (PR), capacity factor, system losses, and the energy injected or consumed. These parameters are used to evaluate the energy efficiency and operational quality of the photovoltaic installation.

II.4.1. Energy production

Energy production represents the total quantity of electrical energy generated by the photovoltaic system over a given period (day, month, or year). This energy depends primarily on the received solar irradiation, installed capacity, climatic conditions, and various system losses **[PSE]**.

The mathematical expression is given as follows:

$$Epv = \sum P(t) \times \Delta t \qquad \text{(II. 1)}$$

Where:

Epv: Energy produced (kWh).

$P(t)$: Instantaneous power (kW).

Δt: Time interval (h).

Energy production is used to:

- Evaluate the overall performance of the installation;
- Calculate the Performance Ratio (PR);
- Estimate revenue generated from electricity sales;
- Determine savings achieved through self-consumption;
- Analyze the profitability of the photovoltaic system.

II.4.2. Performance ratio (PR)

a) **Definition:** The Performance Ratio represents the ratio between the energy actually produced by the system and the energy theoretically available based on the solar irradiation received. It is used to measure all system losses (temperature, cabling, inverter, soiling, mismatch, etc.).

b) **Expression:** The Performance Ratio is defined by the following ratio:

$$PR = \frac{Y_f}{Y_r} \qquad (II.\ 2)$$

Where:

Y_f: Final system yield (kWh/kWp) – Net energy injected divided by the installed peak power.

Y_r: Reference yield (kWh/kWp) – Total incident irradiation divided by standard irradiance (1kW/m2).

c) **Interpretation:** The Performance Ratio (PR) is a dimensionless parameter with a value ranging between 0 and 1 (or 0% and 100%), as detailed in Table II-1.

PR	Interpretation
> 0.85	Excellent
0.75 – 0.85	Good system
0.65 – 0.75	Average
< 0.65	Poor performance

Table II-1: Interpretation of the performance ratio (PR) and its range.

d) **PR in PVsyst:** In PVsyst, the PR is automatically calculated within the simulation results. It appears notably in:

- Main results;

- Energy balance;
- Report final.

PVsyst uses the PR to aggregate the impact of all system losses.

e) Decomposition of the PR (crucial): The PR can be interpreted as the product of the efficiencies related to different types of losses:

$$PR = (1 - \text{optical losses}) \times (1 - \text{thermal losses}) \times (1 - \text{electrical losses}) \quad (\text{II}.3)$$

It therefore depends on the following factors:

- **Optical losses:** Soiling, shading, and reflections.
- **Thermal losses:** Temperature rise of the modules relative to standard conditions.
- **Electrical losses:** Inverter efficiency, resistive cable losses, and losses due to mismatch.

f) Importance of the PR: The PR is a vital indicator used to:

- Compare photovoltaic systems located in different geographical contexts;
- Evaluate the quality of design and installation;
- Detect anomalies or technical issues;
- Validate the accuracy of PVsyst simulations;
- Monitor the actual performance of a photovoltaic array.

II.4.3. Capacity factor

The capacity factor represents the ratio between the energy actually produced by an installation over a given period and the energy it would have produced had it operated at its nominal power continuously throughout that same period.

The expression is given as follows:

$$Fc = \frac{E_{PV}}{P_{nom} \times 8760} \quad (\text{II}.4)$$

Where:

- Fc: Capacity factor (dimensionless or in %).
- E_{pv}: Energy produced over one year (kWh).
- P_{nom}: Installed power (kW).

- 8760: Number of hours in a year (h).

The capacity factor is interpreted in Table II-2, as shown below:

Fc	Interpretation
< 10 %	Low performance
10 % – 20 %	Average
20 % – 30 %	Good photovoltaic system
> 30 %	Highly efficient (excellent conditions or storage)

Table II-2: Interpretation of the Capacity Factor (Fc).

The capacity factor is used to:

- Compare different electricity production technologies;
- Evaluate the actual utilization of a PV system;
- Analyze the productivity of a solar installation;
- Estimate energy profitability.

In PVsyst, the capacity factor generally appears in:

- Main results;
- Summary report;
- Energy balance.

It is directly related to:

- The received solar irradiation;
- System losses;
- The overall efficiency of the installation.

II.4.4. System losses

System losses correspond to the difference between the available solar energy and the electrical energy actually converted by the photovoltaic installation, resulting from various physical, electrical, and environmental phenomena. These losses are represented synthetically by the loss diagram (Figure II-5).

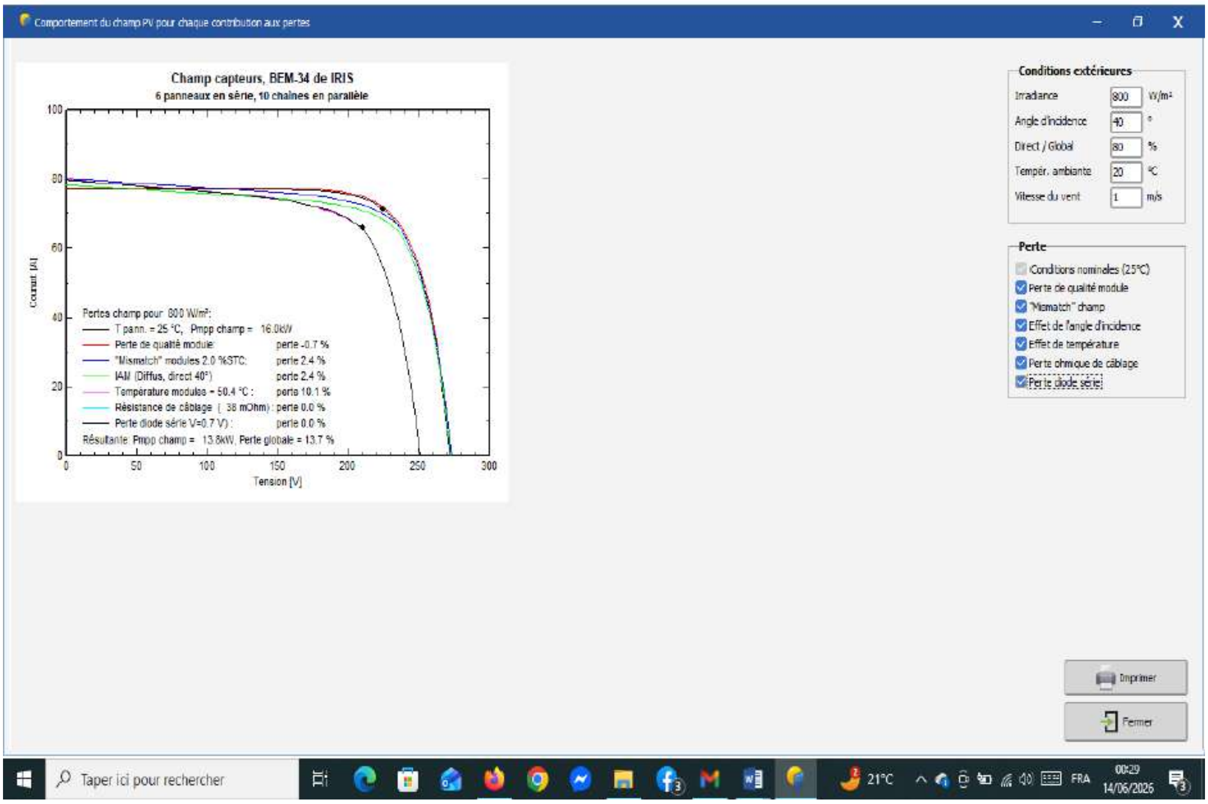


Figure II-5: System loss diagram.

System Losses are divided into several categories:

a) **Optical losses:**

- Reflection at the module surface;
- Incidence angle modifier (IAM) losses;
- Soiling, and shading.

b) **Thermal losses:**

- Increase in module temperature;
- Decrease in efficiency due to heat.

c) **DC electrical losses:**

- Resistive losses in DC cabling;
- Mismatch between modules;
- Diodes and connections.

d) **Inverter losses:**

- DC/AC conversion efficiency;

- Operation outside the optimal operating range.

e) AC losses:

- AC cabling;
- Transformer losses (if applicable).

II.4.5. Injected or consumed energy

This distribution refers to the allocation of electrical energy generated by the PV system between local consumption (self-consumption) and grid injection.

a) Injected Energy (EGrid): The amount of electricity produced by the system and sent to the public grid.

Expression: $EGrid$

Characteristics: The injected energy represents:

- The production sold or exported;
- Dependence on local consumption;
- An important indicator for grid-connected systems.

b) Consumed Energy (EUser / Self-consumption): The portion of photovoltaic energy used directly by local loads before any grid injection.

Expression: $EUser$

Characteristics: It represents:

- Self-consumption
- Reduced dependence on the electrical grid
- Improved system profitability

Energy Balance: The relationship between these energy flows is expressed as:

$$EPV = EUser + EGrid \tag{II.5}$$

In PVsyst, these values allow to:

- Analyze the distribution of generated energy;

- Evaluate the self-consumption rate;
- Estimate revenue from electricity sales;
- Optimize system sizing.

II.5 Conclusion

This chapter has presented the fundamental tools for the design and evaluation of photovoltaic systems, with a particular focus on the PVsyst software, which is widely recognized in the field of photovoltaic simulation. After detailing its history, fields of application, and key functionalities, we examined the essential data required for a reliable simulation, such as meteorological data, the selection of PV modules and inverters, as well as the overall system configuration.

Furthermore, we analyzed the primary parameters and performance indicators necessary for understanding the energy behavior of a PV installation. Energy production, the Performance Ratio (PR), the capacity factor, system losses, as well as injected or self-consumed energy are essential tools for evaluating the efficiency, reliability, and profitability of a photovoltaic system.

Mastery of these tools and indicators enables a rigorous analysis of performance and the optimization of system sizing. The knowledge gained in this chapter will serve as a methodological foundation for the practical study and the analysis of simulation results to be developed in the following chapter.

Chapter III : Case Study, Sizing, and Comparative Analysis

III.1. Introduction

In this chapter, a three-way comparative study will be carried out between the results obtained from manual calculations, those generated through simulations performed using PVsyst software version 7.1.1, and the real data from the existing photovoltaic installation. This approach aims to evaluate the level of agreement between the theoretical, numerical, and experimental methods. It also enables the identification and analysis of possible discrepancies in order to understand their underlying causes and influencing factors. Finally, this analysis leads to the formulation of general conclusions and recommendations for improving the performance and reliability of the studied photovoltaic system.

Before presenting the main work carried out in this study, and in order to move away from the conventional approach generally adopted in Master's theses in Electrical Engineering, we found it useful to dedicate a preliminary section to a brief comparative study of the different versions of the PVsyst software.

This approach aims to highlight the progressive evolution of the software across its different versions by presenting the main features, improvements, and specific enhancements introduced in each one. This analysis will also help to scientifically justify the choice of PVsyst version 7.1.1 used in this work, showing that it represents a relevant compromise between stability, simulation accuracy, functional richness, and ease of use in the field of photovoltaic studies.

III.2. Comparative Study of the Different Versions of PVsyst Software and Justification of the Choice of Version 7.1.1

PVsyst software is one of the most widely used tools in the field of design, simulation, and performance evaluation of photovoltaic systems. Since its creation in 1992 by André Mermoud [PVsyst website], several versions have been developed to improve the accuracy of models, the ergonomics of the interface, and the functionalities intended for engineers and researchers.

III.2.1. Evolution of the Main Versions of PVsyst

Table (III.1) below presents a summary of the main developments and improvements introduced in the different versions of the PVsyst software, highlighting the functional innovations and optimizations implemented over time.

Table III.1. Evolution of the Main Features of PVsyst Software Across Its Different Versions

Version	Main features
PVsyst 6.x	Introduction of an improved 3D environment, support for bifacial systems and multi-orientation configurations.
PVsyst 7.0	Transition to 64-bit architecture, management of an unlimited number of sub-arrays, improvement of the irradiation model and shading calculations, addition of advanced economic tools.
PVsyst 7.1	Complete redesign of simulation reports, improved 3D environment, better handling of half-cell modules and optimizers, more ergonomic and stable interface.
PVsyst 7.2	Improvement of photovoltaic field modeling, new functionalities for trackers and TMY meteorological data.
PVsyst 7.4	Integration of new meteorological databases, improved optimizer management, and correction of numerous simulation issues.
PVsyst 8.x	Advanced and unlimited management of orientations, simultaneous integration of trackers and fixed planes, new 3D features, and introduction of PVsystCLI for simulation automation.

III.2.2. Comparative Analysis

The analysis of the different versions shows that PVsyst has undergone a progressive evolution aimed at improving the accuracy of photovoltaic simulations and the user experience. Version 7.0 represents a major milestone thanks to the adoption of a 64-bit architecture and the improvement of the physical models used in energy calculations.

Version 7.1 represents a particularly significant evolution as it maintains the stability of version 7.0 while introducing several important improvements, including a complete redesign of the final report, enhanced 3D modeling tools, and better support for modern photovoltaic modules such as half-cell modules.

Subsequent versions (7.2 and 7.4) mainly introduce specific improvements and bug fixes, whereas version 8 introduces a new approach to orientation management and advanced features that may be unnecessary for standard academic studies of conventional photovoltaic power plants.

III.2.3. Justification for the Choice of PVsyst Version 7.1.1

As part of this work, PVsyst version 7.1.1 was selected for the following reasons :

- High stability and reliability of simulation results.
- Availability of all necessary tools for the study of grid-connected photovoltaic systems.
- An intuitive user interface that facilitates the modeling of the studied system.
- Generation of detailed and professional reports that can be used in an academic context.
- Compatibility with databases of commonly used photovoltaic modules and inverters.
- Wide usage in research work and photovoltaic engineering studies.

Thus, PVsyst version 7.1.1 constitutes an optimal compromise between performance, simulation accuracy, software stability, and ease of use, which justifies its adoption in this study.

The following figure presents a synthetic representation of the evolution of PVsyst software versions, highlighting the main improvements and features that have been progressively added throughout its development.

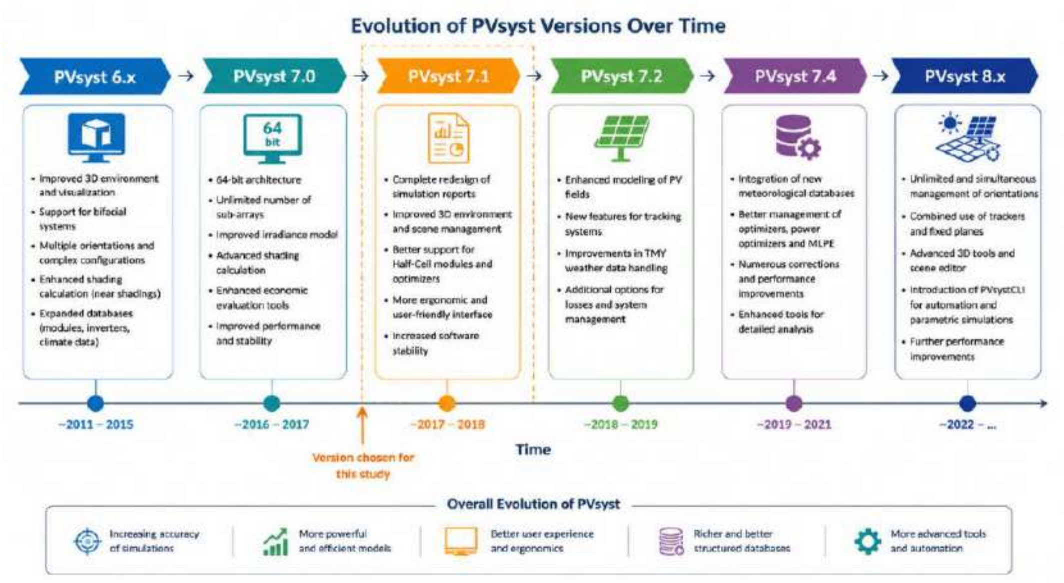


Fig.III.1. Evolution of PVsyst Software Versions and Key Feature Enhancements Over Time. (Source : Author's illustration using AI-based design tools).

III.3. Description of the Study Conducted

This work presents a study of a real photovoltaic installation designed to supply a strategic administrative floor within the SONELGAZ Distribution Directorate in Mila. This floor includes the director's office, the secretariat, as well as the Human Resources Department (HRD) offices. It represents a critical hub within the organization, as it concentrates administrative management activities, coordination, communication, and decision-making processes. The proper functioning of these services is essential to ensure the continuity of the company's operations, human resource management, processing of administrative documents, and the supervision of various activities related to electrical energy distribution.

The implementation of an independent energy source from the public grid aims to ensure service continuity in the event of power outages or disturbances in electricity supply. It also helps secure the operation of computer equipment, communication systems, and management tools that are essential to administrative activities. Furthermore, the integration of a photovoltaic installation contributes to reducing conventional energy consumption, controlling operating costs, and promoting renewable energy in line with SONELGAZ's sustainable development policies.

The objective of this study is to carry out a three-way comparative analysis between the results obtained from manual calculations, those derived from simulation reports generated using PVsyst version 7.1.1, and the actual parameters and characteristics of the existing photovoltaic installation on site. The purpose of this approach is to assess the level of agreement between the theoretical, numerical, and real-world methods. It also enables the identification and analysis of possible discrepancies between the results of manual calculations, the performance predicted by the simulation, and the actual operating conditions, in order to understand their causes and influencing factors. Finally, this comparison leads to the extraction of general conclusions and the formulation of recommendations aimed at improving the performance, reliability, and overall efficiency of the photovoltaic installation.

Figure (III.2) below presents a representation of the studied photovoltaic installation, generated using AI.

Fig.III.2. AI-Generated View of the Studied PV Installation.

The geographical data of the studied PV installation are summarized in the following Table.

Table.III.2. Geographical Data of the Studied PV Installation.

Geographical site	Situation		Albedo (Ground reflectance)
Mila (city), Algeria	Latitude	36.45 °N	0.20
	Longitude	6.26 °E	
	Altitude	487	
	Time zone	UTC+1	

The Albedo value = **0.20** corresponds to the ground reflectance coefficient, meaning that the ground surface reflects **20%** of the incident solar radiation and absorbs **80%**. This parameter is taken into account by the software when evaluating the radiation received by the photovoltaic modules, particularly in relation to ground reflection effects. For more details, refer to Appendix A.

The city of Mila is characterized by a hot-summer Mediterranean climate (Csa type according to the Köppen classification). It is located at an altitude ranging between 450 and 500 m above sea level, with an average altitude of approximately 470 m [Topographic], which leads to a slight moderation of temperatures compared to nearby coastal areas. The climate is marked by hot and dry summers, with average summer temperatures ranging between 30 and 35 °C, while heat waves can exceed 40 °C. Winters are cool to cold and relatively humid, with average temperatures generally varying between 4 and 15 °C. Rainfall is mainly concentrated between October and April, whereas the summer season is characterized by almost total dryness [ONM].

Thanks to a good level of annual sunshine (an average of 7 to 9 hours per day, corresponding to approximately 2500 to 3200 hours per year) and favorable average solar irradiation (around 4.5 to 5.5 kWh/m²/day, equivalent to approximately 1600 to 2000 kWh/m²/year), the city of Mila offers suitable climatic conditions for energy applications, particularly photovoltaic systems.

The table below summarizes the main electrical loads considered in this study, indicating for each device its nominal power and estimated usage, which makes it possible to establish the overall consumption profile of the site.

Table.III.3. Recommended Electrical Load Profile and Energy Consumption of the Studied Site.

Electrical device	Power [W]/unit	Number	Operating time [h/day]	Energy [Wh/day]
Lighting	30	28	9	7560
TV/PC/Mobile	150	11	9	14850
Household appliances	1200	2	2	4800
Refrigerator	6.25 (0.15 kWh/day)	1	24	151
Air conditioner	1200	5	5	30000
Printers	300	4	4	4800
Others	5	16	24	1920
Stand-by consummers	10	-	24	240
Total daily energy [Wh/day]				**64321**
Total monthly energy [kWh/mth]				1929.630

III.4. Manual Calculation Study

III.4.1. Total Daily Energy Consumption

Et=64321Wh/jr=64.321 kWh/day

III.4.2. Energy to be Generated by the Panels

E_p is the energy that must be produced by the solar panels per day, and it is given by :

$$E_p = \frac{E_t}{k} \quad \text{(III.1)}$$

K is the system efficiency, a coefficient that takes into account the total system losses (in cables, batteries, etc.), i.e. :

$$E_p = E_t + losses \quad \text{(III.2)}$$

In our study, the system coefficient is **K = 0,75**. Therefore :

$$E_p = \frac{64.321}{0.75} = 85.761\ kWh$$

III.4.3. Required Nominal (Peak) Power of the PV System

The required nominal (peak) power P_C of the PV system (all panels) is given by :

$$P_C = \frac{E_p}{G} \quad \text{(III.3)}$$

G is the number of equivalent sunshine hours per day, corresponding to daily irradiation expressed in Peak Sun Hours (PSH). One PSH corresponds to an irradiation of 1 kW/m² over 1 hour, i.e., 1 kWh/m²/day.

In our study, we use G=5G. Therefore :

$$P_C = \frac{85.761}{5} = 17.1522\ kWp$$

III.4.4. Number of PV Modules

In the context of the policy supporting local production between national institutions, we have chosen to use locally manufactured photovoltaic modules with a nominal power of Pn_pan = 340 Wp. This choice is justified by several reasons :

- Availability and wide distribution in the local market ;
- Technological reliability and proven performance ;
- Good compromise between cost and efficiency ;
- Suitability for the requirements of the study and the simulations carried out.

Furthermore, this average power of 340 Wp was selected because using lower-power modules would require a higher number of panels to achieve the same installed capacity, which would lead to an increase in the required surface area as well as greater installation complexity (support structure, wiring, and spatial occupation).

The number of panels can be calculated as follows :

$$N_{Pan} = \frac{P_c}{P_{n\_Pan}} \quad \text{(III.4)}$$

Thus, we obtain : $N_{Pan} = \frac{171522}{340} = 50.447$

Since this is a non-integer value, and in order to ensure that the required power is met, the result is rounded up. Thus, the number of photovoltaic modules is set to **51 panels**.

III.4.5. Installed Power

The installed power can be expressed as :

$$P_{inst} = N_{Pan} * P_{n\_Pan} \tag{III.5}$$

Thus : $P_{inst} = 51 * 340 = 17.34\ kWp$

III.4.6. Calculation of the Drawn Current

The current drawn by the system (the current supplied by the photovoltaic generator) can be determined from the fundamental electrical power relationship :

$$P = VI \Longrightarrow I = \frac{P}{V}$$

Where *P* represents the installed power and *V* the system voltage. In this study, the DC voltage of the photovoltaic system is set to Vsyst_DC=509.52 V. Therefore, we obtain :

$$I = \frac{17340}{509.52} = 34.032\ A$$

III.4.7. PV Module Arrangement

a) Number of Panels in Series

Considering a maximum power point voltage of V_{mpp}=37.33 V under STC (Standard Test Conditions), the number of panels connected in series is obtained by dividing the nominal system voltage by V_{mpp} :

$$N_{Pan\_ser} = \frac{V_{syst\_DC}}{V_{mpp}} \tag{III.6}$$

Thus : $$N_{Pan\_ser} = \frac{509.52}{37.33} = 13.64$$

Since the number of modules must be an integer, and in order to ensure proper system operation ($V_{Pan} \leq V_{mpp}$), the selected value is **14 modules connected in series**.

To verify : $$V_{Pan} = \frac{V_{syst\_DC}}{N_{Pan\_ser}} = \frac{509.52}{14} = 36.39 < 37.33$$

b) Number of strings

The number of strings (panels in parallel) corresponds to the ratio between the total number of panels and the number of panels in series :

$$N_{string} = \frac{N_{Pan}}{N_{Pan\_ser}} \quad \text{(III.7)}$$

$$N_{string} = \frac{51}{14} = 3.64$$

Since this value must be an integer, two solutions are possible : 3 or 4 strings.

For 3 strings : 14 × 3 = 42 modules, so the installed power is : 42*340=14.34 kW

Which is lower than the required system power Pc=17.1522 kWp.

For 4 strings : 14 × 4 = 56 modules, so the installed power becomes : 56*340=19,04 kWp, which is higher than the required system power.

Consequently, the selected configuration is **4 strings**, corresponding to a total of **56 modules**, and the installed power is therefore reassessed at **19.04 kWp**. The excess power is intended for battery charging.

Furthermore, a new estimate of the total drawn current is carried out :

$$I_{tot} = \frac{19040}{509.52} = 37.36\ A$$

The branch current, corresponding to the current flowing through a photovoltaic module string, is also determined :

$$I_{branch} = \frac{I_{tot}}{N_{string}} \quad \text{(III.8)}$$

$$I_{branch} = \frac{37.36}{4} = 9.34\ A$$

III.4.8. Inverter Selection

Following a preliminary analysis of the characteristics of the inverter actually installed in the photovoltaic plant, it was found that they are consistent with the results obtained from the manual calculations. Therefore, a similar choice was adopted in order to remain close to the real system configuration. Two identical inverters of the Hybrid Grid Inverter type, model SUN-10K-SG04LP3-EU, were selected in a master–slave configuration. In this type of architecture, the admissible power ratings of both inverters are combined to cover the total power of the photovoltaic array. Thus, the master inverter provides a power of 13 kW, while the slave inverter handles the remaining portion, i.e., 4.1522 kW (17.1522 − 13 = 4.1522 kW), corresponding to the total required system power.

Table.III.4. Characteristics of the selected inverter

Parameter	Value
Type	Hybrid Grid Inverter
Model	SUN-10K-SG04LP3-EU
Maximum PV input power	13 kW
Rated PV input voltage	550 V (160–800 V)
Battery voltage	48 V DC (40–60 V)
Configuration	Master–Slave (2 identical inverters)

III.4.9. Number of Batteries

a) Choice of Autonomy

Initially, the choice of battery type was made in agreement with the designer of the actual power plant, opting for lithium technology. This choice is mainly justified by several advantages :

- Although its initial cost is higher than that of lead-acid batteries, lithium batteries offer a longer lifespan.
- Operating and maintenance costs are lower in the long term.
- They provide a high energy density, resulting in reduced size and weight for the same storage capacity.
- This aspect is particularly important due to the space constraints available on the site.

On the other hand, due to the lack of precise information regarding the autonomy initially selected by the planner, it was defined by taking into account the following elements :

- The directorate is already connected to the public electricity grid.
- The continuity of service provided by the grid is generally satisfactory.
- The average annual solar potential is relatively high in the region.

A reduced autonomy (N_{days}) is therefore considered sufficient in this context. Thus, an autonomy of **8 hours** has been selected, corresponding to a standard working day in Algeria, i.e., approximately N_{days} = **0.3 day**.

b) Energy capacity to be stored in the battery system

The energy capacity to be stored in the battery system is determined from the daily energy consumption and the selected autonomy, according to the following relation :

$$E_{stock} = E_t * N_{days} \tag{III.9}$$

Thus : $$E_{stock} = 64.321 * 0.3 = 19.2963\ kWh$$

c) Choice of battery

The choice of the battery must first be made by considering the characteristics of the selected inverter. According to the datasheet of the SUN-10K-SG04LP3-EU inverter, the acceptable battery voltage is 48 V DC, with an operating range between 40 V and 60 V. In order to remain consistent with the configuration of the actual installation, a $LiFePO_4$ battery with a capacity of 100 Ah and a nominal voltage of 51.2 V was selected. This capacity can be considered average for this type of application. The nominal battery voltage lies well within the operating range accepted by the inverter, ensuring electrical compatibility. Furthermore, for $LiFePO_4$ batteries, an efficiency of η = 0.95 and a depth of discharge (DOD) of 80% were adopted, in accordance with commonly accepted values in the technical literature and manufacturers' specifications.

d) Required Energy Capacity of the Battery Bank

The required energy capacity of the battery bank is determined by the following expression :

$$E_{bank\_bat} = \frac{E_{stock}}{\eta * DOD} \tag{III.10}$$

Thus : $$E_{bank\_bat} = \frac{19.2963}{0.95*0.8} = 25.39\ kWh$$

e) Energy Stored in a Battery

The energy stored in a battery is calculated from its nominal capacity and nominal voltage, according to the following relation :

$$E_{bat} = C_{bat} * V_{bat} \tag{III.11}$$

Thus : $$E_{bat} = 100 * 51.2 = 5.12\ kWh$$

f) Total Number of Batteries

The total number of required batteries is determined by dividing the total energy of the battery bank by the energy stored in a single battery, according to the following relation :

$$N_{bat} = \frac{E_{bank\_bat}}{E_{bat}} \tag{III.12}$$

Thus : $$N_{bat} = \frac{25.39}{5.12} = 4.96$$

In practice, N_{bat} is generally rounded up to the nearest integer to ensure the required storage capacity is met. Therefore, we select $\boldsymbol{N_{bat} = 5}$ **batteries**.

g) Number of Batteries in Series

The number of batteries in series is determined based on the inverter's acceptable voltage and the nominal voltage of a single battery, according to the following relation :

$$N_{bat\_ser} = \frac{V_{bat\_invert}}{V_{bat}} \tag{III.13}$$

Thus : $$N_{bat\_ser} = \frac{48}{51.2} = 0.94$$

Therefore, **one battery in series** is selected ($\boldsymbol{N_{bat\_ser} = 1}$).

h) Number of Battery Strings (Parallel Branches)

The number of battery strings (parallel branches) is determined by dividing the total number of batteries by the number of batteries in series, according to the following relation :

$$N_{strng\_bat} = \frac{N_{bat}}{N_{bat\_ser}} \tag{III.14}$$

Thus : $$N_{strng\_bat} = \frac{5}{1} = 5$$

Therefore, the battery bank consists of **5 strings**, each string containing a **single battery in series**.

i) Alternative Selection Test

Considering a 200 Ah – 51.2 V battery, with an efficiency of η=0.95 and a depth of discharge DOD=80% :

$$E_{bat} = 200 * 51.2 = 10.24\ kWh$$

$$N_{bat} = \frac{25.39}{10.24} = 2.48 \approx 3 \text{ batteries in parallel.}$$

In conclusion, the 100 Ah battery option is preferred in order to avoid a more unfavorable scenario in the event of battery failure. Indeed, in a system based on 100 Ah batteries, the loss of a single battery out of five represents only 20% of the total storage capacity. In contrast, in the case of a system using 200 Ah batteries, the failure of a single battery results in a loss of approximately 33.3% of the total capacity, which is more detrimental to service continuity and system reliability.

III.5. Simulation Study with PVsyst

In this section, PVsyst software version 7.1.1 is used to evaluate the degree of agreement with the manual calculations performed previously and, if possible, to obtain more accurate results. Furthermore, this simulation work gives this thesis the role of a practical user guide, providing detailed information and illustrations that are not usually sufficiently covered in standard documentation, making it a useful reference for beginner students as well as researchers.

The simulation of the photovoltaic system using PVsyst software version 7.1.1 is carried out according to the steps presented below, as the software requires an Internet connection for proper operation.

- Double-click the PVsyst software shortcut icon (Fig.III.3) to open the main interface of the software. The startup screen of this version appears as shown in Figure (III.4) below.

Fig.III.3. Shortcut icon of PVsyst software.

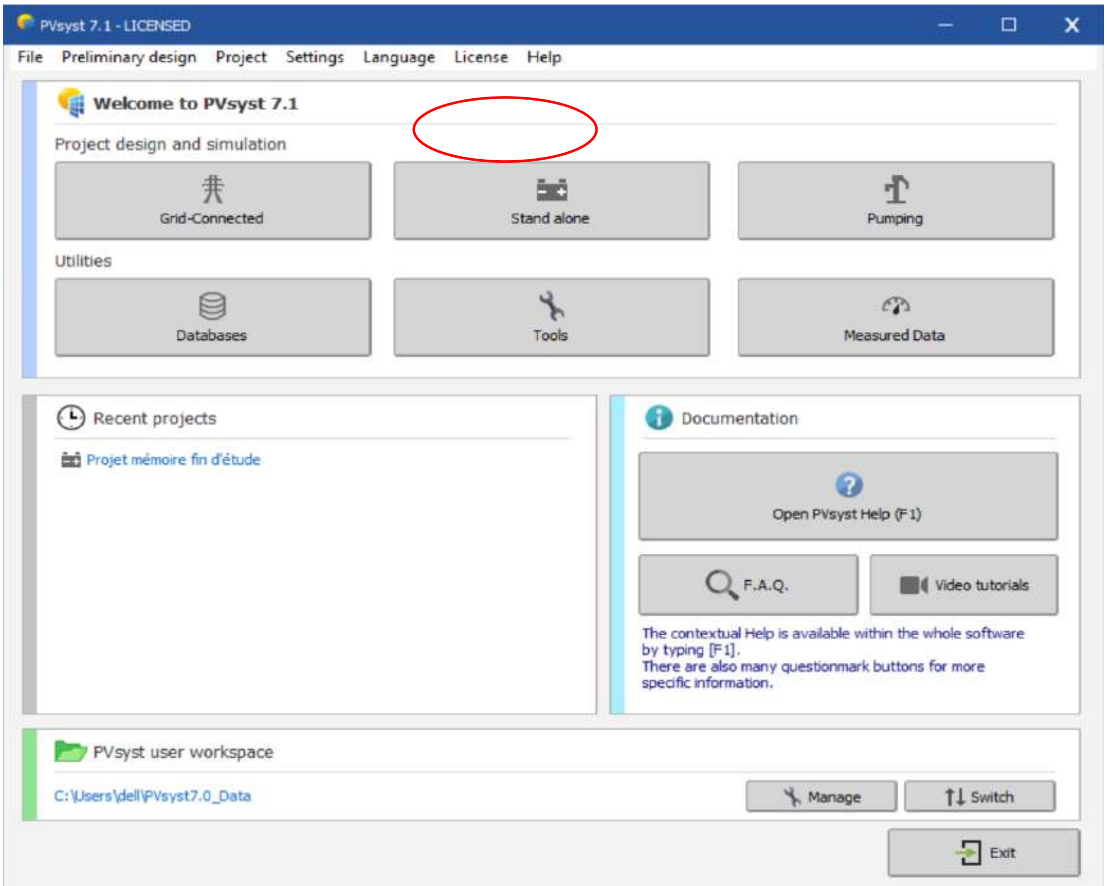


Fig.III.4. Startup screen of PVsyst software V7.1.1.

- Click on the « **Stand alone** » button to access the configuration mode of an off-grid photovoltaic system, corresponding to the studied installation (see the button highlighted in red in Figure III.4 above).
- Click on « **New project** » to create a new simulation project (see the button highlighted in red in Figure III.5 below).
- Enter the project name.

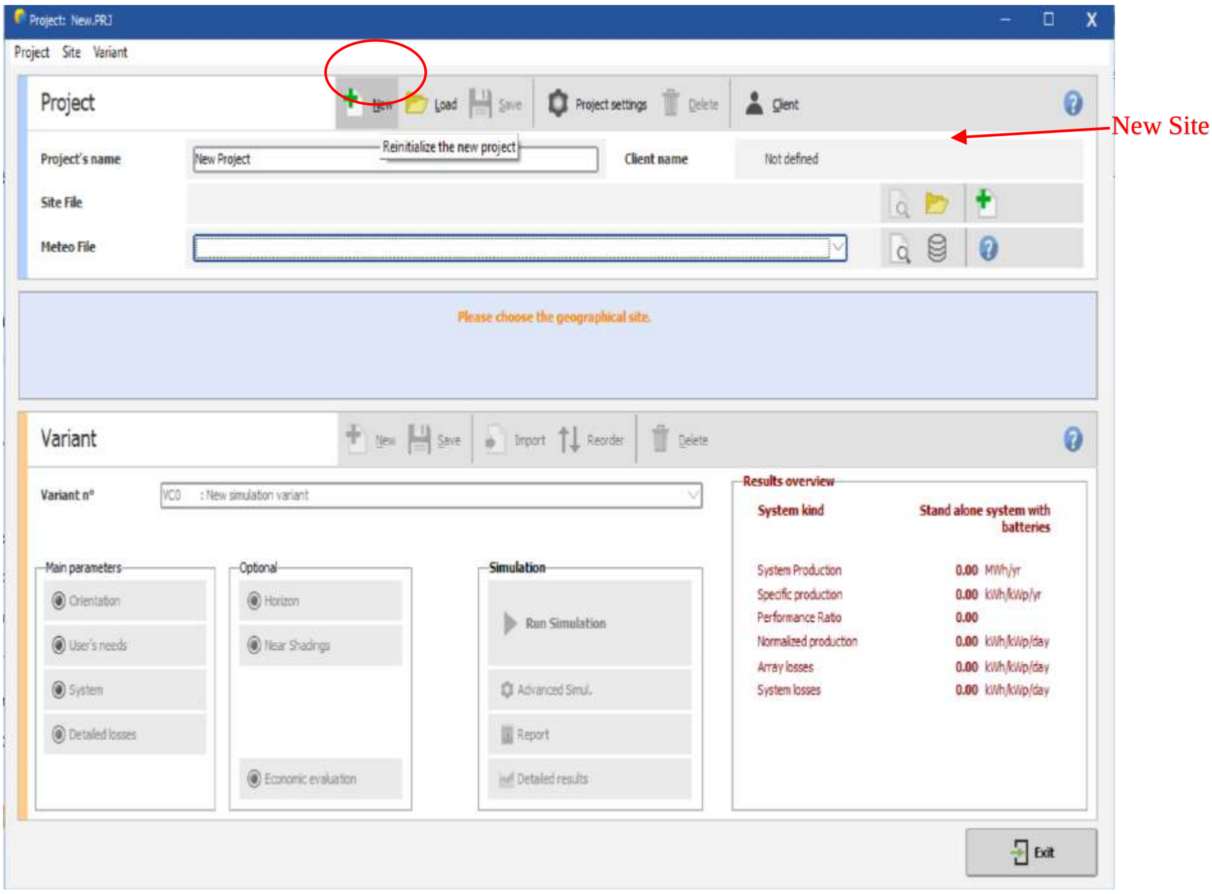


Fig.III.5. Main configuration and simulation interface in PVsyst.

- Click on « **New Site** » ; a world map will appear. Then search for the desired location or enter its geographic coordinates (36.45°N, 6.26°E), and select the exact location by clicking on the map so that a point indicating its precise position appears (see Figure III.6 below).
- Verify and confirm the parameters of the selected site in the « **Selected Point** » tab on the right side of the window, then validate by clicking « **Accept Selected Point** ».

- Next, the « **Geographical Coordinates** » sub-window appears (see Figure III.7 below) ; then select the meteorological database from the list located on the right side of the window. In this study, the **Meteonorm 7.3** database was chosen due to its reliability and the accuracy of its meteorological data.
- Click on « **Import** » to open the « **Monthly Meteo** » sub-window. In the panel on the right, under the « **Irradiation Units** » section, select the unit « **kWh/m²/day** » (see Figure III.8).
- Return to the « **Geographical Coordinates** » sub-window, then click on the « **Sun paths** » button to display the sun path diagram corresponding to the studied site (see Figure III.9).
- Finally, click on « **OK** » to save the project.

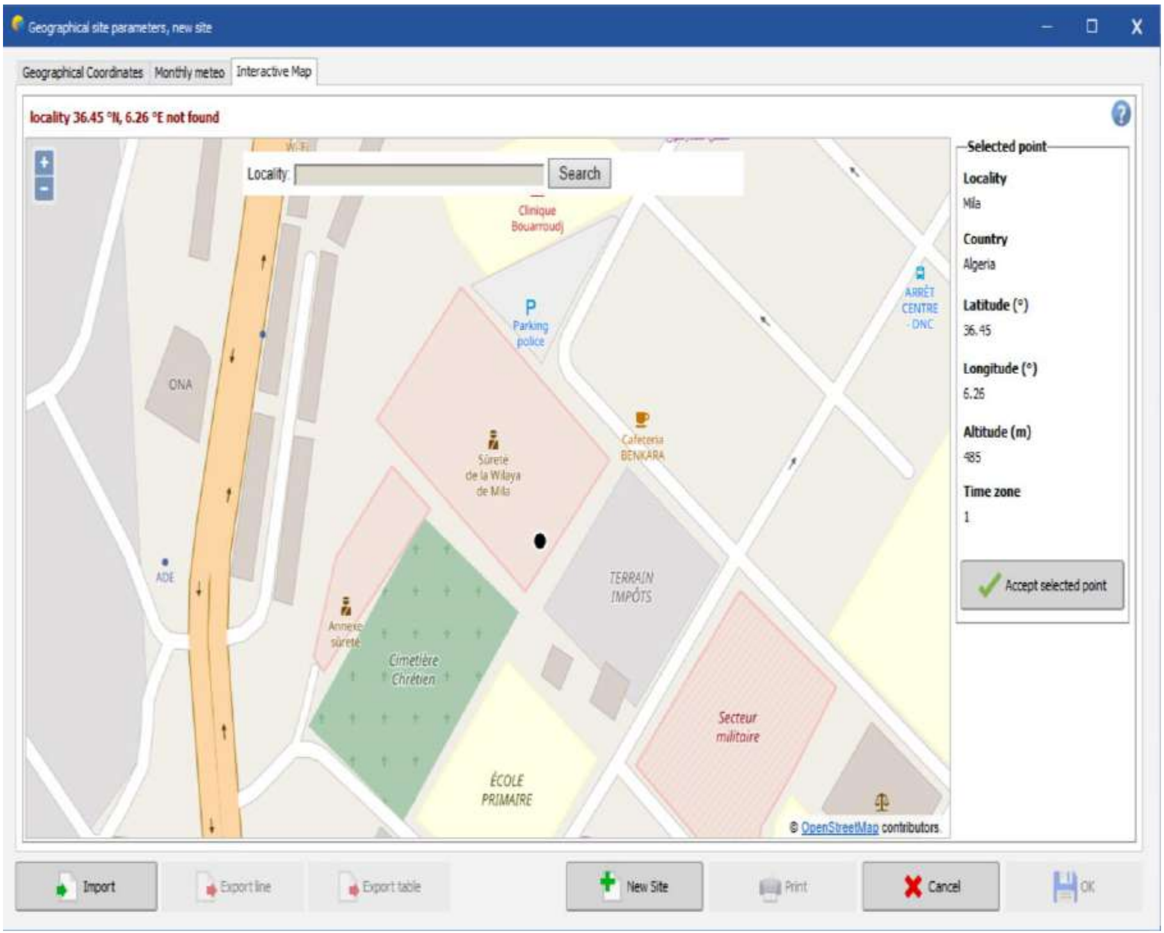


Fig.III.6. Geographical Site Parameters Window.

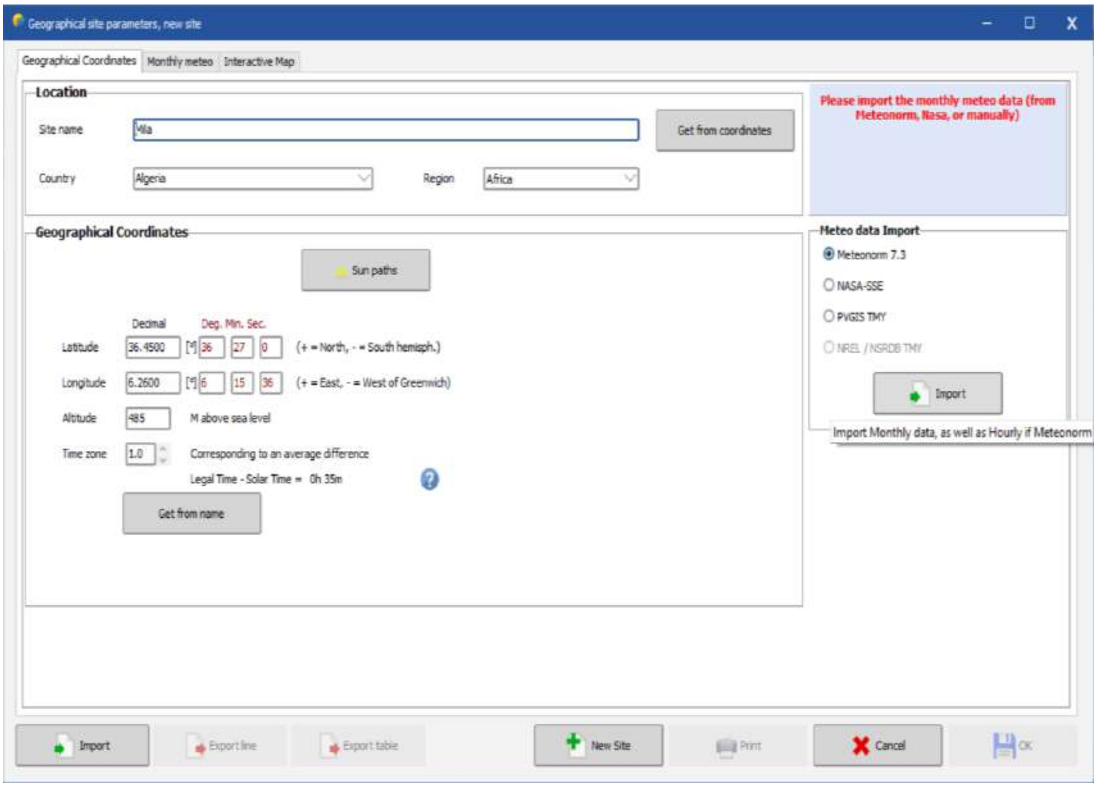


Fig.III.7. Selection of the meteorological database.

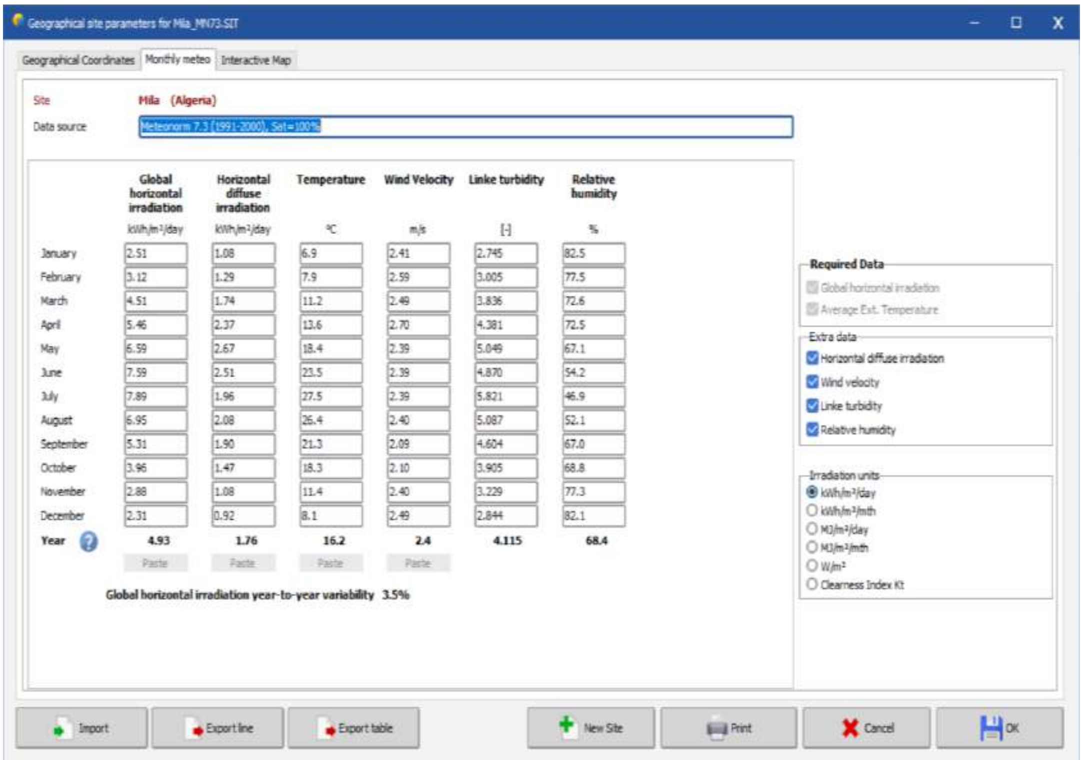


Fig.III.8. Monthly Meteo Window.

PVsyst V7.1.1

Geographical Site
Mila
Algeria

Situation

Latitude	36.45 °N
Longitude	6.26 °E
Altitude	485 m
Time zone	UTC+1

Monthly Meteo Values

Source Meteonorm 7.3 (1991-2000), Sat=100%

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
Horizontal global	2.51	3.12	4.51	5.46	6.59	7.59	7.89	6.95	5.31	3.96	2.88	2.31	4.93	kWh/m²/day
Horizontal diffuse	1.08	1.29	1.74	2.37	2.67	2.51	1.96	2.08	1.90	1.47	1.08	0.92	1.76	kWh/m²/day
Extraterrestrial	4.87	6.36	8.10	9.90	11.09	11.57	11.35	10.40	8.82	6.97	5.28	4.45	8.27	kWh/m²/day
Clearness Index	0.514	0.491	0.557	0.552	0.594	0.656	0.696	0.668	0.602	0.568	0.545	0.520	0.596	ratio
Ambient Temper.	6.9	7.9	11.2	13.6	18.4	23.5	27.5	26.4	21.3	18.3	11.4	8.1	16.2	°C
Wind Velocity	2.4	2.6	2.5	2.7	2.4	2.4	2.4	2.4	2.1	2.1	2.4	2.5	2.4	m/s

Solar paths at Mila, (Lat. 36.4500° N, long. 6.2600° E, alt. 485 m) - Legal Time

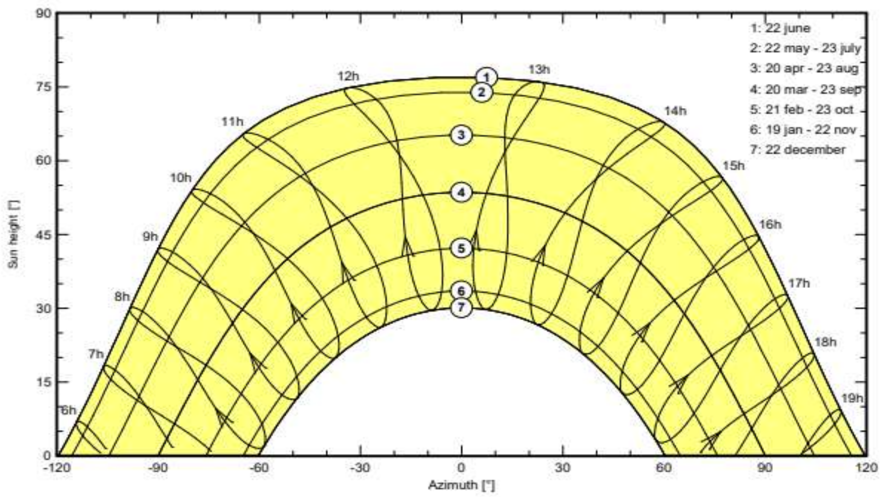


Fig.III.9. Diagram of the sun path at the studied site.

- After saving the project, the software automatically returns to the main configuration and simulation interface (Figure III.5). In the **« Main Parameters »** tab, click on **« Orientation »** to open the orientation configuration window.
- In the orientation configuration window (see Figure III.10), select the **« Yearly Irradiation Yield »** option under the **« Optimization with respect to »** section. Next, in the **« Field Parameters »** section, gradually vary the **« Plane Tilt »** angle and record the corresponding value of **« Global on Collector Plane »** each time. When this value reaches its maximum, stop adjusting the tilt angle and retain the corresponding value as the optimal tilt angle. In the present study, the optimal tilt angle obtained is **34°**. Finally, click **« OK »**.

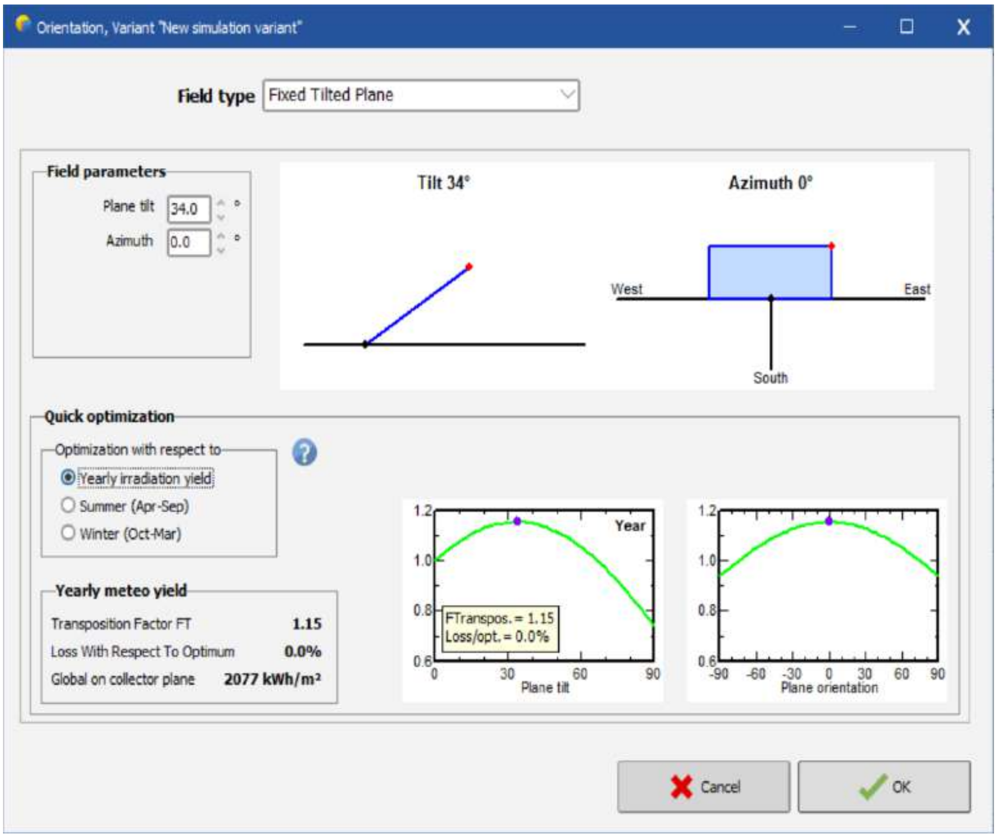


Fig.III.10. Orientation Configuration Window.

Explanation of the Procedure

This procedure makes it possible to determine the tilt angle that provides the best annual exposure of photovoltaic modules to solar radiation. Indeed, the amount of solar energy intercepted by the panel surface depends directly on its orientation and tilt angle. The optimal angle corresponds to the one that maximizes the "Global on Collector Plane" irradiance, thereby promoting the highest possible annual energy production of the photovoltaic generator.

- From the main interface, and within the « **Main Parameters** » tab, click on « **User's Needs** » to access the « **Daily Use of Energy** » window.
- In the « **Consumption** » section, enter all the values of the electrical load parameters listed in Table III.2 (see Figure III.11).
- Click on the « **Hourly Distribution** » section, then specify the operating hours of each load. It should be noted that the time wheel is divided into 48 segments, each corresponding to a 30-minute interval (see Figure III.12). Click on « **Show others** » to display the remaining time wheels. Finally, click « **OK** ».

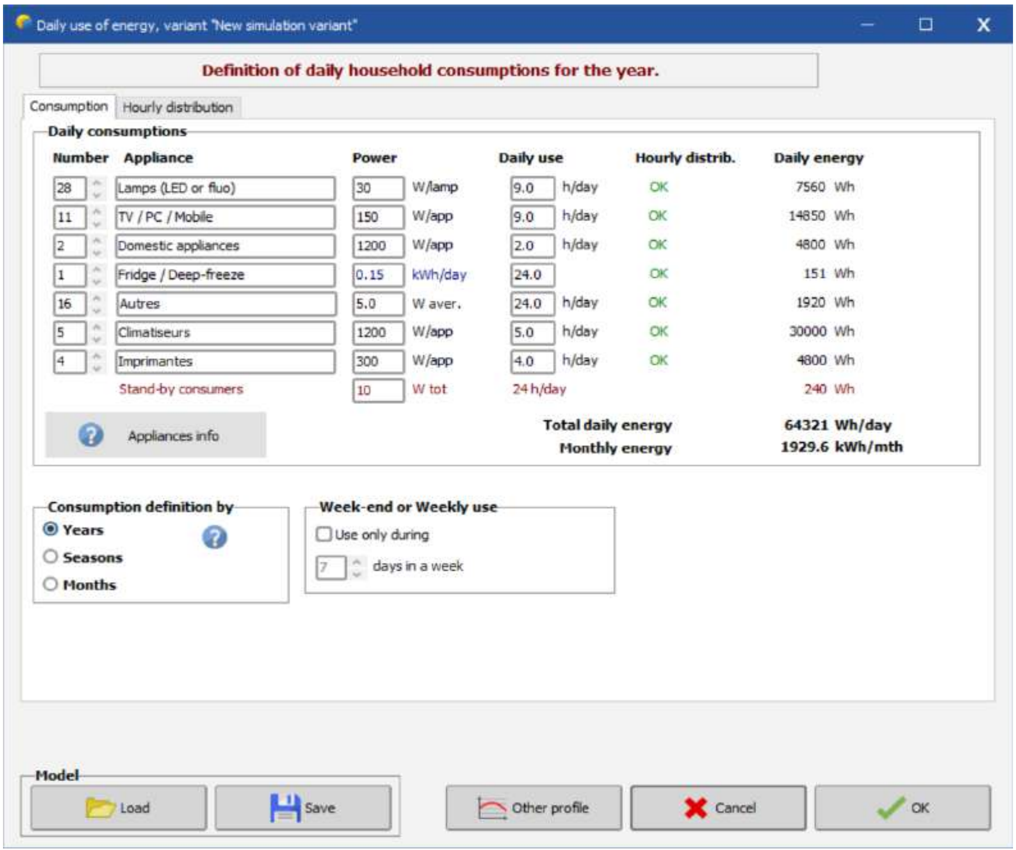


Fig.III.11. Consumption Section in the « Daily Use of Energy » Window.

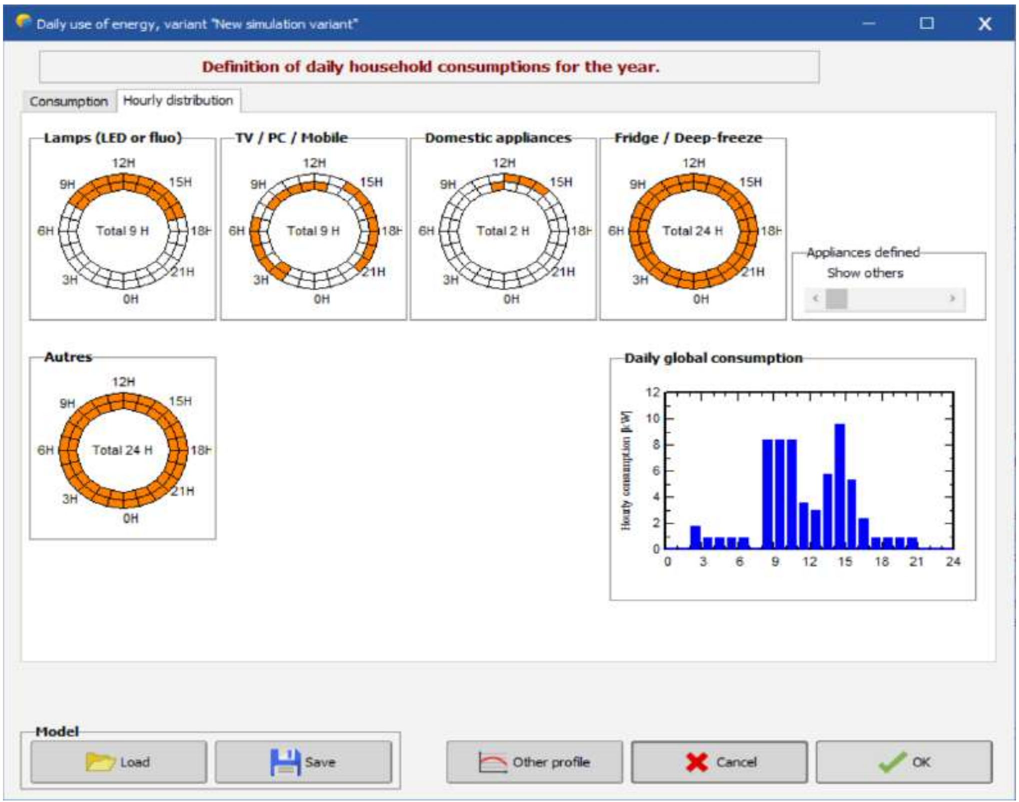


Fig.III.12. Hourly Distribution Section in the « Daily Use of Energy » Window.

- From the main interface, select « **System** » to open the « **Stand-alone System Definition** » window (see Figure III.13).

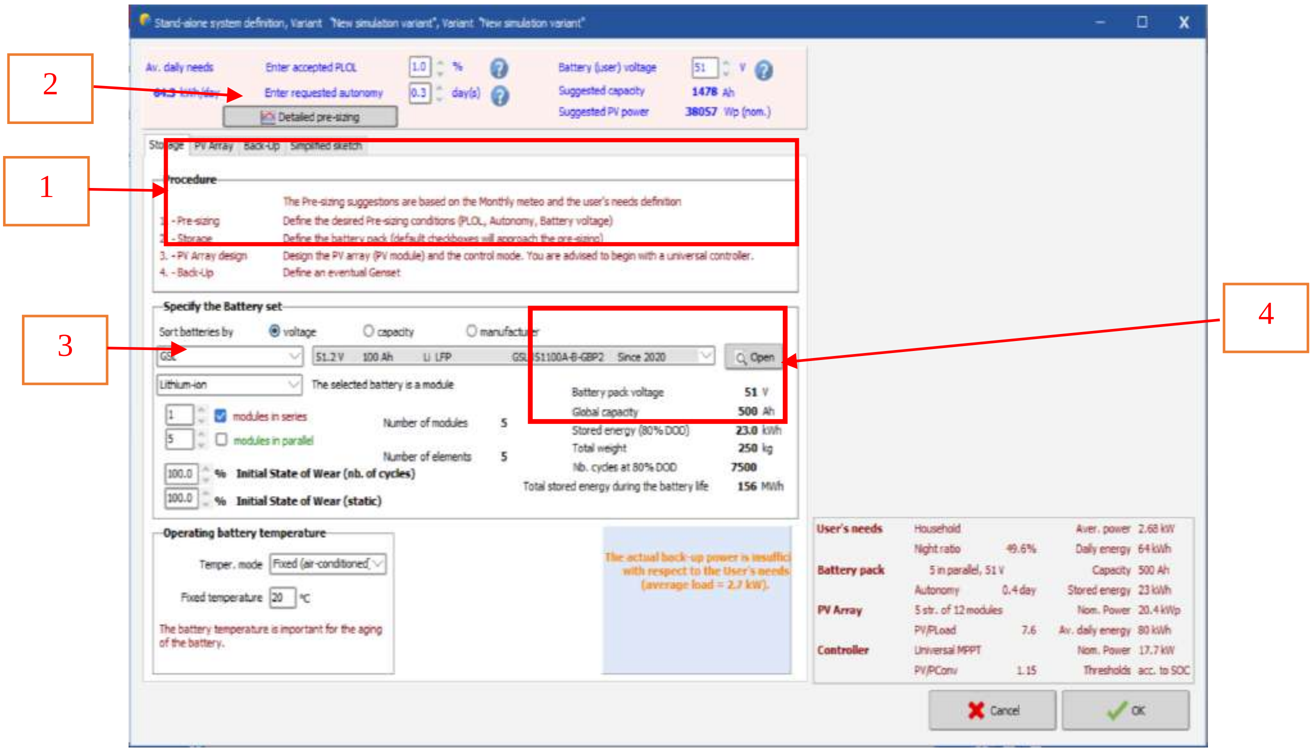


Fig.III.13. « Storage » section in « Stand-alone System Definition » Window.

The section labeled 1 in the previous figure describes the four steps of the « **Stand-alone System Definition** » process.

- Click on the « **Detailed Pre-sizing** » button, indicated by number 2 in the previous figure, to access the « **PV Array Detailed Sizing Tool** » window in order to define the desired pre-sizing conditions (PLOL, autonomy, and battery voltage) (see Figure III.14).

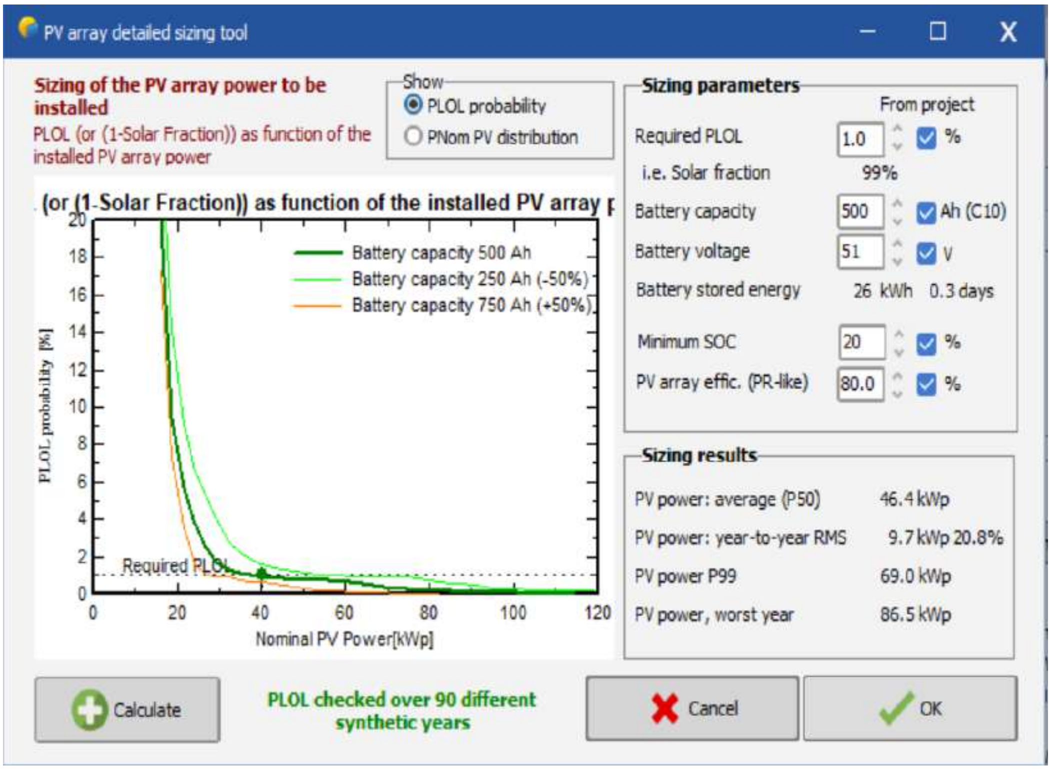


Fig.III.14. PV Array Detailed Sizing Tool Window.

☞ In the « **Show** » section, select « **PLOL Probability** ». In the « **Sizing Parameters** » section, enter the desired pre-sizing parameters. In this study, the following values were adopted : **PLOL = 1%**, a battery voltage of **51.2 V** (since the software only accepts integer values, **51 V** was used), and a battery capacity of **500 Ah**, corresponding to the total capacity of the battery bank providing an autonomy of **0.3 day**. Finally, click « **OK** ».

Explanation of the Instruction

The PLOL (**Probability of Loss of Load**) value is determined based on the ranges of values given in the following table :

Table III.5. PLOL Value Ranges According to the Type of Photovoltaic System

PV system type	PLOL (%)
Off-grid (stand-alone system relying only on batteries)	0.1 - 1
Grid-connected (batteries used only as backup)	0 - 1
Hybrid (solar, battery, grid)	1 - 5

Since the photovoltaic system of the studied installation is of hybrid type, the selected PLOL value is **1%**, meaning that the system allows only **1% of time without sufficient power supply**, corresponding to a **99% reliability level**.

- In the **« Storage »** section, under the **« Specify the battery set »** area, select the **« Voltage »** option in **« Sort batteries by »**.
- Since the required battery type (100 Ah, 51.2 V) is not available in the **« Specify the battery set »** list, it must be created. To do so, first select any battery from the list, then click **« Open »** ; the **« Definitions for a Battery »** window will then appear (see Figure III.15).
- In the **« Basic Data »** section, enter the data as shown in Figure III.15, in accordance with the characteristics of the battery type used in the real photovoltaic installation, with particular emphasis on the essential settings, namely enabling the **« Per element »** option and setting the **« Nb of cells in series / in parallel »** in the **« Basic Parameters »** section to **1 and 1**.
- Then click on **« Copy to table »**, followed by **« OK »**.

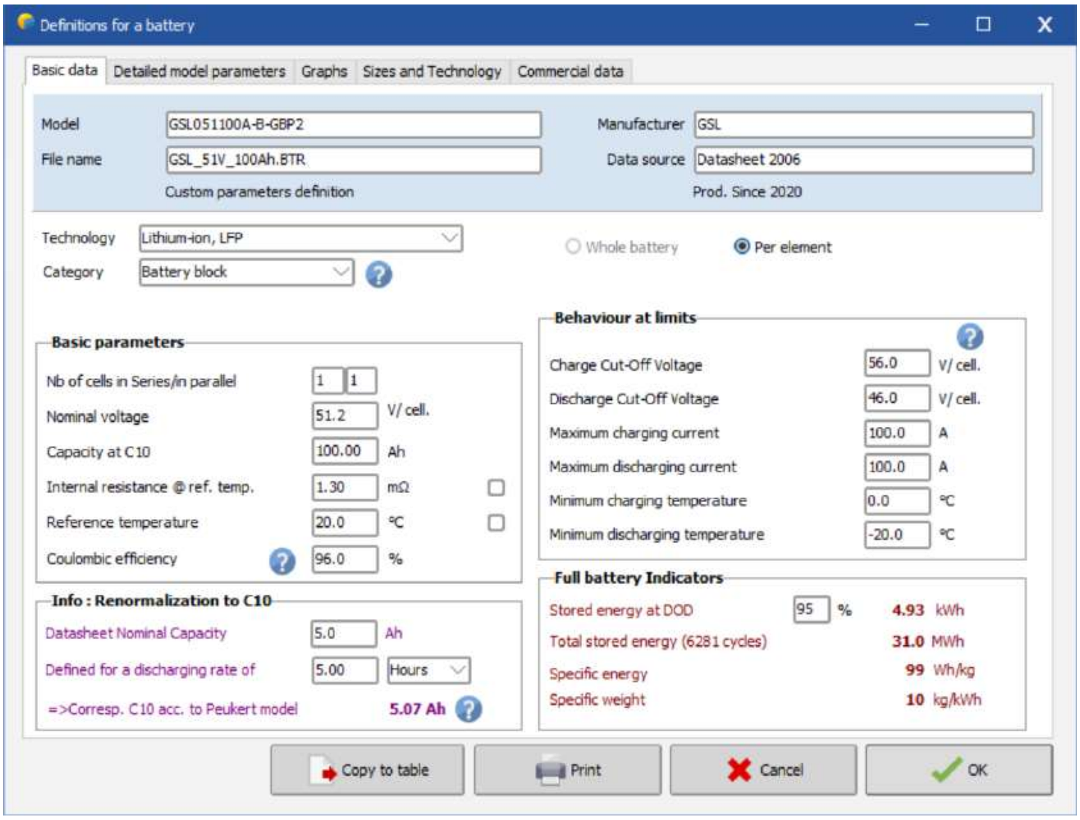


Fig.III.15. « Definitions for a Battery » Window.

Explanation of the Instruction

In this way, a new battery file is created. This file, which contains all the parameters defined by the user, is automatically saved in the PVsyst component directory. For example, on our workstation, it is stored in the following folder : **C:\Users\Dell\PVsyst7.0\ComposPV\Batteries**. By accessing this location, it is possible to verify the presence of the file corresponding to the newly created battery. Moreover, this battery automatically appears in the list of available batteries within the software, confirming its successful registration and integration into the PVsyst database.

As illustrated by indicator (3) in Fig. III.13, PVsyst proposes an optimal battery bank configuration consisting of **a single battery in series and five parallel branches (5 strings)**. This configuration perfectly matches the one obtained from the previous manual calculations, providing additional validation of the sizing results. Furthermore, indicator (4) presents the main electrical characteristics of the battery bank proposed by the software, including its nominal voltage, capacity, and total stored energy.

☞ After configuring the battery bank, the next step is to access the **« PV Array »** section in order to enter the parameters of the photovoltaic modules selected for the study. The corresponding interface is illustrated in Fig. III.16 below.

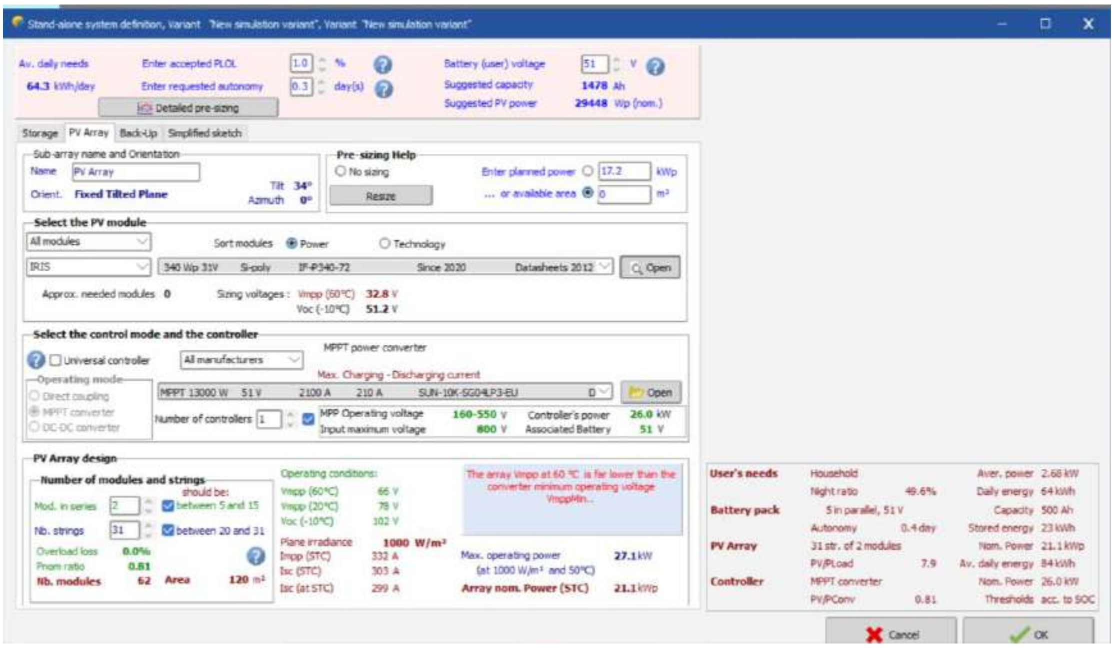


Fig.III.16. « PV Array » section in « Stand-alone System Definition » Window.

- In the « **Select the PV Module** » section, the « **Sort modules** » option provides two choices, including « **Power** », which should be selected in order to organize the list of modules according to their nominal power and thereby facilitate the selection of the required module.
- Since the photovoltaic module selected for this study (**IFRI-SOL, IF-P340-72, 5BB Polycrystalline Module 330 Wp**) is not available in the « **Select the PV Module** » list, it must be manually created in the PVsyst database. To do so, first temporarily select any PV module from the list, then click « **Open** ». This action opens the « **Definition of a PV Module** » window, from which it is possible to modify or create a new module by entering its technical specifications, as shown in Fig. III.17.
- In the same « **Definition of PV Module** » window, within the « **Sizes and Technology** » section, it is necessary to check the « **Cells** » subsection and enter the following values : **In series = 72** and **In parallel = 1**, in order to correctly define the electrical configuration of the photovoltaic module (see Figure III.18).

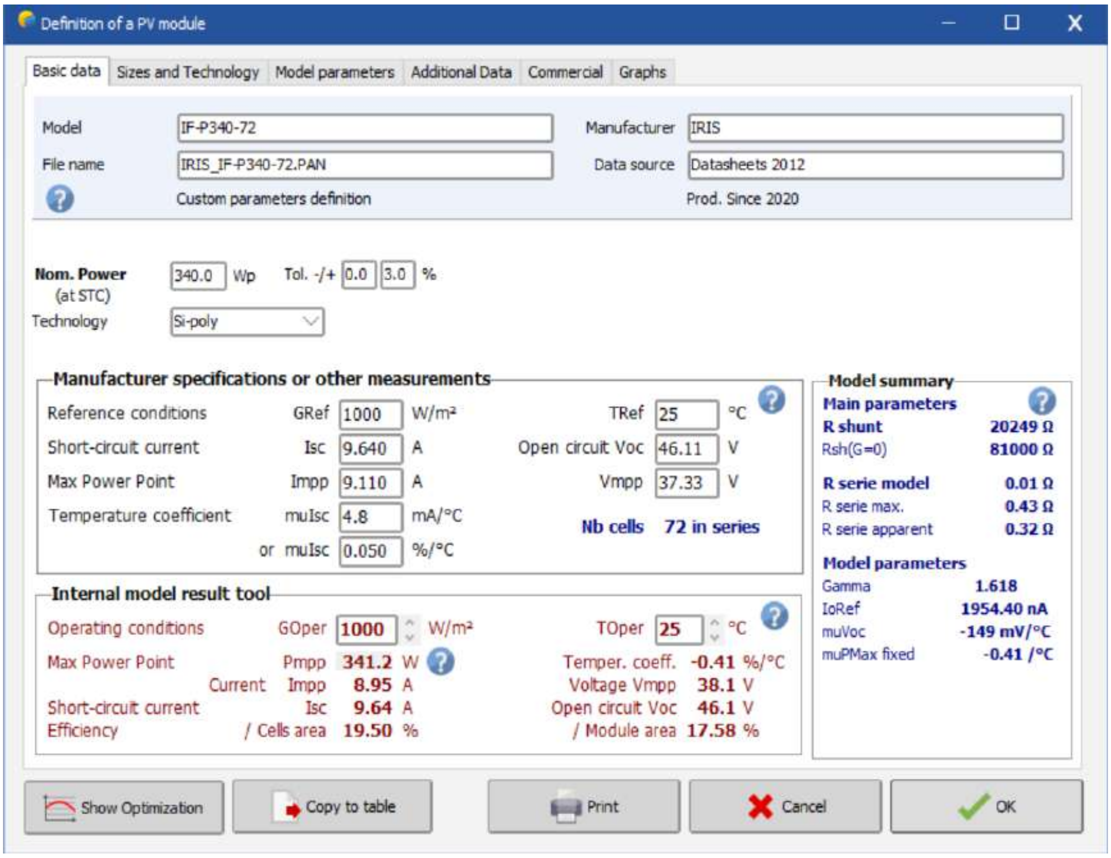


Fig.III.17. « Definition of a PV Module » Window.

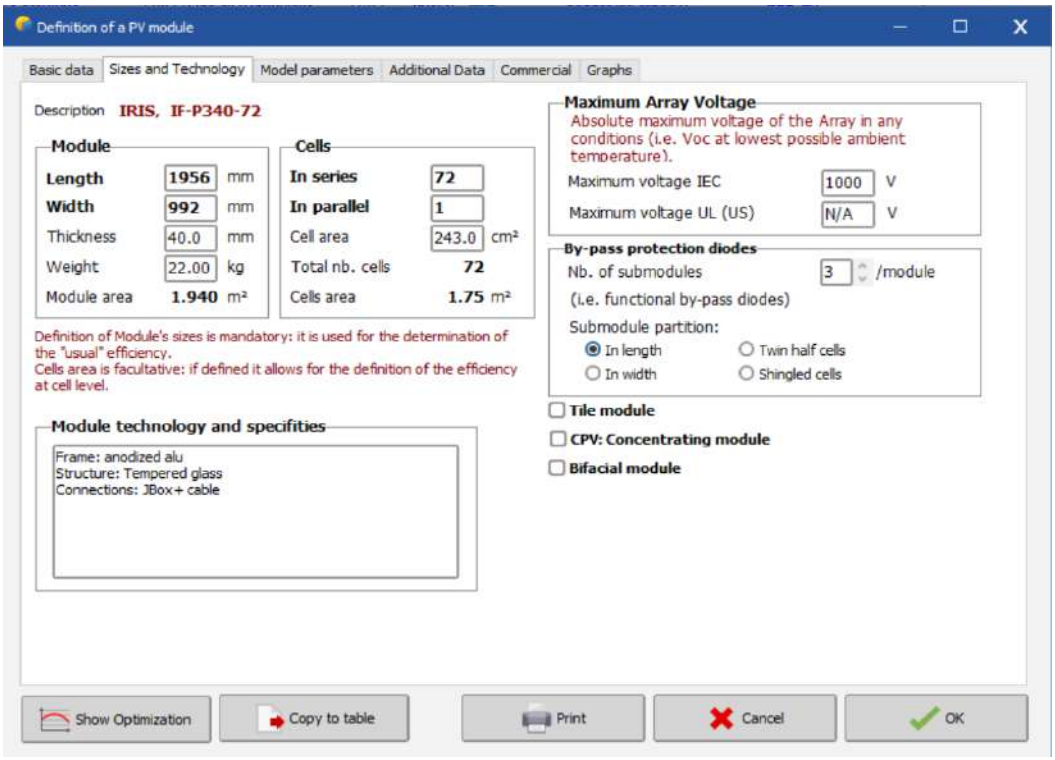


Fig.III.18. « Sizes and Technology » section in « Definition of a PV Module » Window.

☞ Access the **« Graphs »** section, then in the **« Curve type »** area select **« Current vs Voltage »**. Next, in the **« Curve parameter »** section, check **« Incident irradiance »**. Finally, in the **« Main parameters »** section, set the temperature to **25°C** in order to comply with Standard Test Conditions (STC), as illustrated in Fig. III.19.

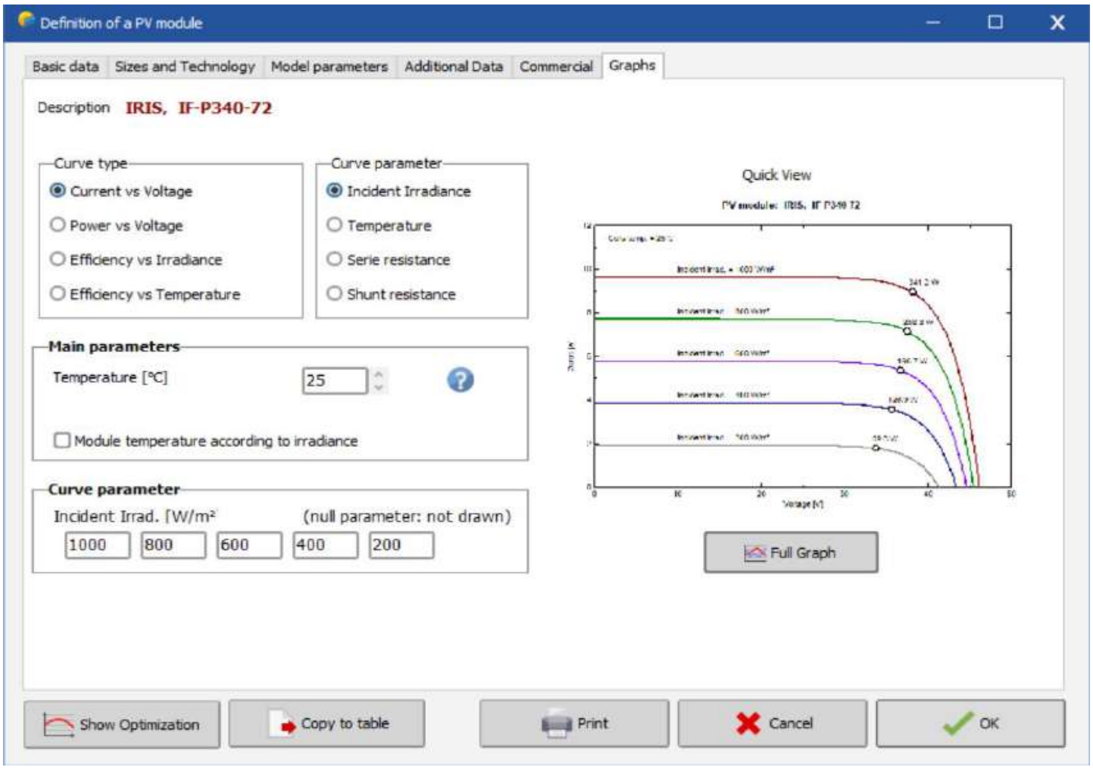


Fig.III.19. « Graphs » section in « Definition of a PV Module » Window.

☞ Click the **« Full graph »** button in order to clearly visualize the current-versus-voltage graph of the photovoltaic module that we are going to create (see Fig. III.20).

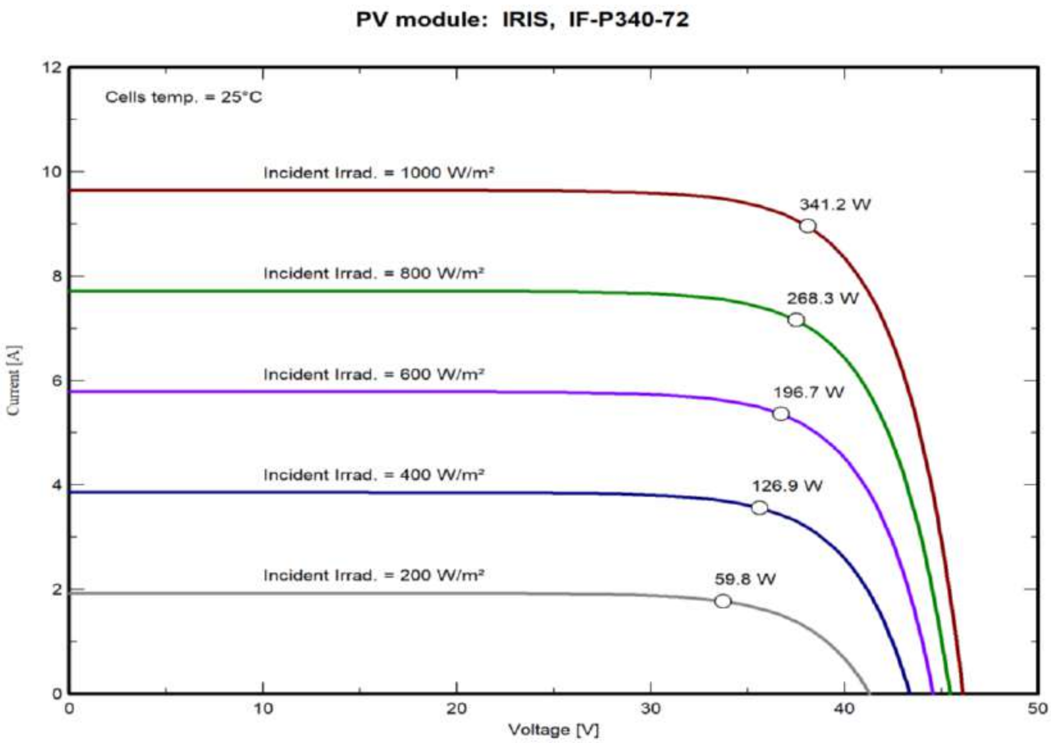


Fig.III.20. I–V Characteristic of the Photovoltaic Module to be Designed.

The analysis of the I–V curve presented in Fig. III.20, obtained under Standard Test Conditions (STC) at a temperature of 25°C, highlights the electrical behavior of the designed photovoltaic module. For an incident irradiance of 1000 W/m², a Maximum Power Point (MPP) is observed, corresponding to a power output of 341.2 W. The coordinates of this point are approximately 9.11 A for the current and 37.33 V for the voltage. These values correspond respectively to the current *Impp* and the voltage *Vmpp* at the maximum power point, although a precise verification with the manufacturer's data is necessary. Furthermore, the power obtained at the MPP (341.2 W) is very close to the module's nominal power (340 Wp), which confirms the consistency of the simulated model and validates the correct sizing of the photovoltaic module to be designed.

- ☞ After verifying the consistency of all parameters of the photovoltaic module to be designed, click the **« OK »** button to validate and save the entered settings.

The newly created photovoltaic module automatically appears in the list of available modules within the software, confirming the successful registration of the module as well as its correct integration into the PVsyst database.

- ☞ In the **« Select the control mode and the controller »** section, it is necessary to search the list for the inverter type used in the real installation, namely the **Hybrid Grid Inverter (SUN-10K-SG04LP3-EU)**, taking into account the parameters already defined in Table III.3. This ensures consistency between the simulation model and the actual equipment of the photovoltaic system.

Since the parameters of the inverter actually installed in the plant were not available in the PVsyst database, a first approach consisted in manually creating the inverter model, as was previously done for the batteries and photovoltaic modules. However, this approach proved difficult, as the software requires the input of a large number of additional technical parameters that are not provided in the manufacturer's datasheet or are expressed using terminology different from that used in PVsyst. This limitation led to the results presented in Figure III.16 above.

The analysis of these results shows that the software proposed a configuration of only **2 modules in series and 31 parallel strings**, which appears impractical and does not correspond to the actual architecture of the studied photovoltaic generator. Moreover, PVsyst explicitly indicated an incompatibility related to inverter sizing, showing that certain input parameters did not allow a valid system configuration to be achieved. However, the software simultaneously provided recommended sizing ranges, namely a **number of modules in series between 5 and 15 and a number of parallel strings between 20 and 31**. These indications served as a relevant technical reference for revising the system configuration.

In order to ensure consistency of the simulation and to overcome the limitations related to the absence of the exact inverter model, the **« Universal Controller »** option was selected. This solution makes it possible to generically represent the overall behavior of the energy management system while maintaining a reliable modeling of the energy exchanges within the installation. This choice is justified by the unavailability of the actual controller in the software library, as well as by the differences in terminology observed between the manufacturer's documentation and the parameters required by PVsyst, making a direct modeling approach difficult to implement and exploit.

Based on this, the final sizing of the photovoltaic array was carried out by simultaneously considering the recommendations provided by PVsyst and the total nominal power of the photovoltaic generator. The selected configuration corresponds to **12 modules in series and 5 parallel strings (a total of 60 modules)**. This choice ensures an operating voltage compatible with the inverter's MPPT range while respecting the system power constraints. Moreover, after adopting this configuration and the universal controller, the previously reported error messages in the software disappeared, confirming the technical consistency and validity of the adopted sizing for this simulation (see Figure III.21).

- ☞ Click on the **« Simplified Sketch »** section to visualize the typical architecture proposed by PVsyst for the studied stand-alone photovoltaic system (see Fig. III.22).

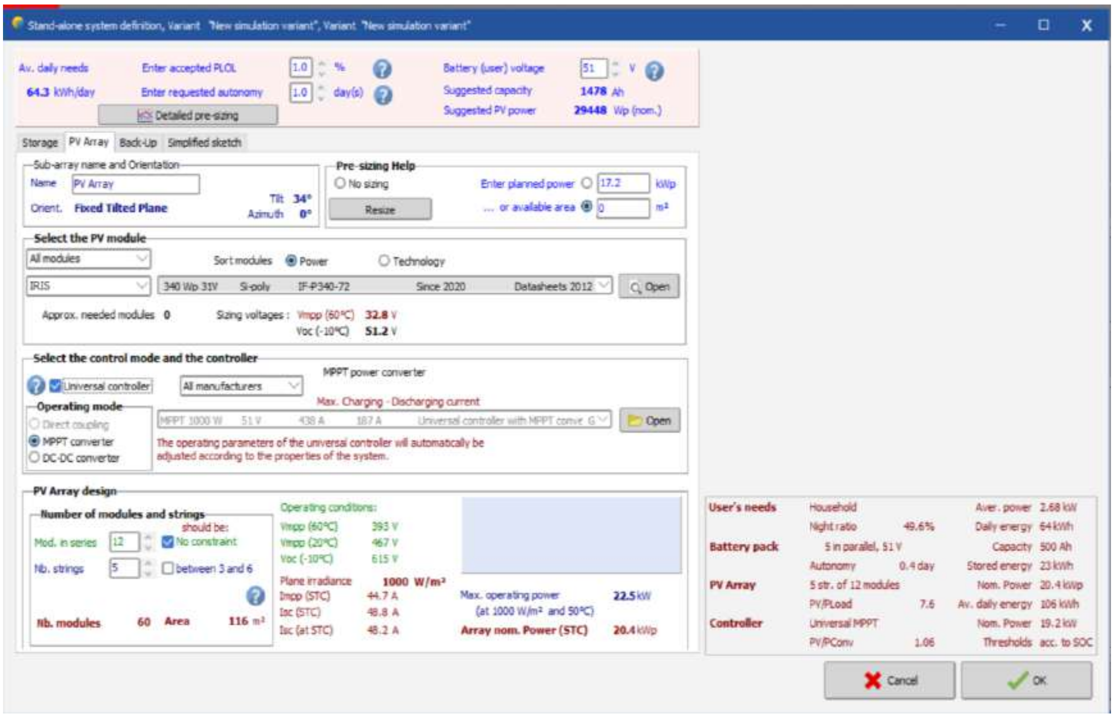


Fig.III.21. Final configuration of the « PV Array » section in the « Stand-alone System Definition » window.

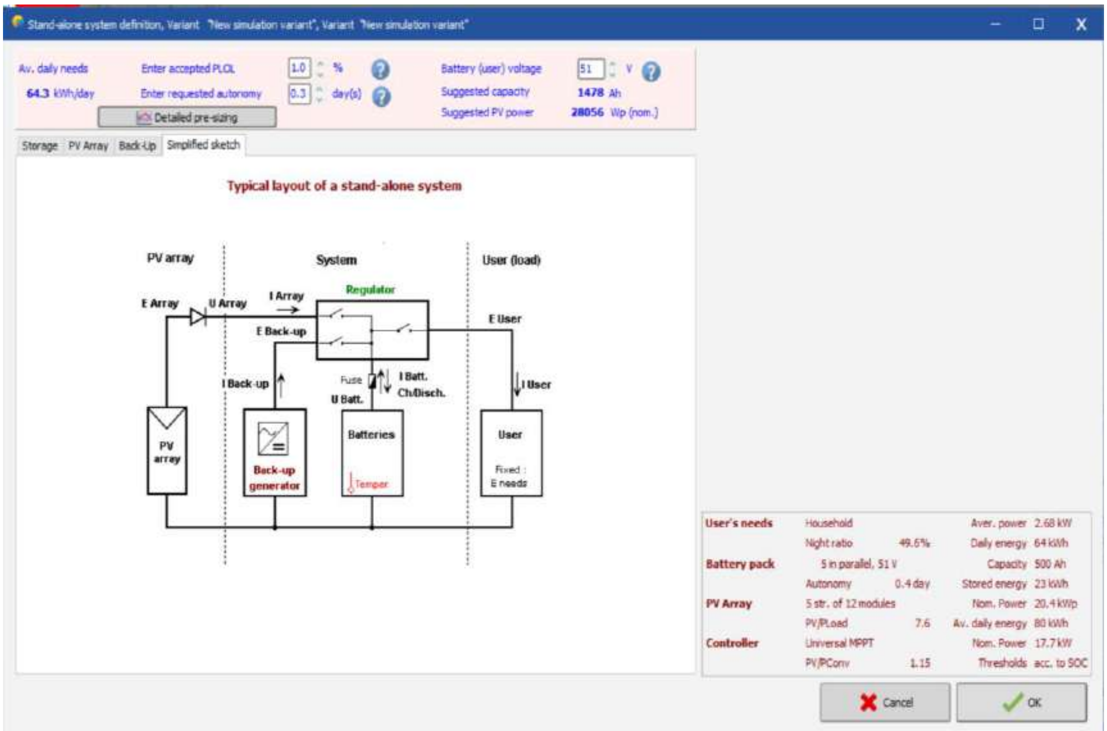


Fig.III.22. Typical architecture proposed by PVsyst for the studied stand-alone photovoltaic system.

- After completing the main steps in the configuration and simulation window (Fig. III.5), click the « **Run simulation** » button to start the simulation. The simulation results are summarized in Figure III.23 below.
- Click on « **Report** » to obtain a detailed report. The generated report for our study is included in **Appendix B**.

Fig.III.23. Overall results window.

III.6. Comparative Analysis and Validation of the Obtained Results

In order to validate the performed sizing and assess the accuracy of the obtained results, a comparative analysis is carried out between the theoretical calculations, the simulation results generated by PVsyst, and the actual data of the photovoltaic installation. The table below presents a comparative summary of the main results obtained.

Table III.6. Comparative Summary of the Main Obtained Results.

Parameter	Theoretical calculations	PVsyst simulation	Real PV installation data
Altitude	487	485	487

Autonomy	0.3	0.4	NA
Panel tilt angle	NC	34	35
Total number of panels	56	60	60
Panels in series	14	12	10
Panel strings	4	5	6
Total current [A]	37.36	NS	NA
String current [A]	9.34	NS	9.64
Installed power [kWp]	19.04	20.4	20.4
Total number of batteries	5	5	4
Batteries in series	1	1	1
Battery strings	5	5	4

NB : NA (Not Available) ; NC (Not Calculated) ; NS (Not Simulated).

It should be noted that the characteristics and data of the different components of the actual installation are presented in **Appendix C**, in the form of tables and screenshots.

The results obtained from the manual calculations, those from the simulation carried out using PVsyst, and the data from the actual photovoltaic installation are very close. This strong agreement allows, on the one hand, the validation of the relevance of the sizing of the real installation and, on the other hand, confirms the reliability and performance of the PVsyst software used in this study.

However, some slight differences can be observed between the simulation results and the real data. These discrepancies are mainly due to the fact that the software database does not include all the exact brands, models, and characteristics of the components used in the real installation, particularly the batteries, photovoltaic modules, and inverters.

III.7. Conclusion

In this chapter, we carried out a comparative study between the results obtained from manual calculations, those obtained through simulation using PVsyst version 7.1.1, and the actual data of the studied photovoltaic installation. This comparison made it possible to assess the consistency between the different approaches and to validate the performed sizing. The obtained results were found to be very close, which confirms the reliability of both the sizing and the models used. Moreover, the use of PVsyst proved to be simple and efficient, saving a considerable amount of time compared to manual calculations while providing accurate and rapid results.

General Conclusion

General Conclusion

The main objective of this work was the study, sizing, and performance evaluation of a photovoltaic installation designed to supply electrical energy to an administrative site belonging to the SONELGAZ Distribution Directorate of Mila. This study is part of the current energy transition context and the promotion of renewable energy sources, aiming to reduce dependence on conventional energy resources while preserving the environment.

First, the theoretical foundations of photovoltaic solar energy were presented. Fundamental concepts related to solar radiation, the operation of photovoltaic cells, the electrical characteristics of modules, and the various stages involved in the sizing of a photovoltaic system were studied. This analysis made it possible to better understand the parameters influencing energy production and the key criteria required for designing an efficient system.

Second, photovoltaic system design and evaluation tools were examined using the PVsyst software. The different input data required for simulation were analyzed, including meteorological data and the characteristics of photovoltaic modules, batteries, and inverters. The main performance indicators, such as energy production, Performance Ratio (PR), capacity factor, and system losses, were also presented in order to ensure a reliable assessment of system performance.

Finally, a practical case study was carried out on a real photovoltaic installation located at the SONELGAZ Distribution Directorate of Mila. The system was sized based on the site's energy demand, and a detailed simulation was performed using PVsyst software. The obtained results were then compared with theoretical calculations and the actual characteristics of the installed system.

The comparative analysis showed very good agreement between the manual calculations, the PVsyst simulation results, and the real data of the studied system. The observed deviations remain small and are mainly explained by differences between the actual installed components and those available in the software databases. This close agreement confirms the validity of the adopted sizing methodology as well as the reliability of PVsyst in evaluating photovoltaic system performance.

The obtained results also demonstrate that the climatic conditions of the Mila region are particularly favorable for the exploitation of solar photovoltaic energy. The studied system exhibits satisfactory performance and represents an effective solution for reducing conventional energy consumption and improving the energy security of the site.

For future work, it would be interesting to include a detailed economic analysis taking into account investment, operation, and maintenance costs, as well as an environmental assessment to quantify greenhouse gas emission reductions achieved through the use of solar energy. The integration of smart energy management systems and the use of more advanced photovoltaic technologies could also be explored in order to further improve overall system performance.

In conclusion, this study highlights the importance of rigorous sizing and numerical simulation in the design of photovoltaic installations. It also confirms the essential role that solar energy can play in meeting future energy needs and in supporting the sustainable development of administrative and industrial infrastructures in Algeria.

APPENDIX A

In solar simulation software such as PVsyst, albedo mainly affects :

- Bifacial photovoltaic systems (Bifacial PV) ;
- The calculation of ground-reflected radiation (Reflected Irradiance) ;
- The energy production from the rear side of bifacial modules.

Table A.1. Common Albedo Values

Surface type	**Approximate albedo**
Dark asphalt	0.05 – 0.15
Bare soil	0.15 – 0.25
Green grass	0.15 – 0.30
Light sand	0.30 – 0.45
Light concrete	0.30 – 0.50
Fresh snow	0.70 – 0.90

APPENDIX B

Version 7.1.1

PVsyst - Simulation report

Stand alone system

Project: Projet mémoire fin d'étude

Variant: New simulation variant

Stand alone system with batteries

System power: 20.40 kWp

Mila - Algeria

Author

Project summary

Geographical Site		**Situation**		**Project settings**	
Mila		Latitude	36.45 °N	Albedo	0.20
Algeria		Longitude	6.26 °E		
		Altitude	487 m		
		Time zone	UTC+1		

Meteo data
Mila
Meteonorm 7.3 (1991-2000), Sat=100% - Synthetic

System summary

Stand alone system — **Stand alone system with batteries**

PV Field Orientation		**User's needs**	
Fixed plane		Daily household consumers	
Tilt/Azimuth	34 / 0 °	Constant over the year	
		Average	64 kWh/Day

System information

PV Array		**Battery pack**	
Nb. of modules	60 units	Technology	Lithium-ion, LFP
Pnom total	20.40 kWp	Nb. of units	5 units
		Voltage	51 V
		Capacity	500 Ah

Results summary

Available Energy	34047 kWh/year	Specific production	1669 kWh/kWp/year	Perf. Ratio PR	30.80 %
Used Energy	12909 kWh/year			Solar Fraction SF	54.98 %

Table of contents

General parameters

Stand alone system — **Stand alone system with batteries**

PV Field Orientation

Orientation

Fixed plane

Tilt/Azimuth 34 / 0 °

Models used

Transposition Perez

Diffuse Perez, Meteonorm

Circumsolar separate

User's needs

Daily household consumers

Constant over the year

Average 64 kWh/Day

PV Array Characteristics

PV module

Manufacturer	IRIS
Model	IF-P340-72
(Custom parameters definition)	
Unit Nom. Power	340 Wp
Number of PV modules	60 units
Nominal (STC)	20.40 kWp
Modules	5 Strings x 12 In series
At operating cond. (50°C)	
Pmpp	18.37 kWp
U mpp	412 V
I mpp	45 A

Battery

Manufacturer	GSL
Model	GSL051100A-B-GBP2
Technology	Lithium-ion, LFP
Nb. of units	5 in parallel
Discharging min. SOC	10.0 %
Stored energy	23.0 kWh
Battery Pack Characteristics	
Voltage	51 V
Nominal Capacity	500 Ah (C10)
Temperature	Fixed 20 °C

Controller

Universal controller	
Technology	MPPT converter
Temp coeff.	-5.0 mV/°C/Elem
Converter	
Maxi and EURO efficiencies	97.0 / 95.0 %

Battery Management control

Threshold commands as	SOC calculation
Charging	SOC = 0.96 / 0.80
Discharging	SOC = 0.10 / 0.35

Total PV power

Nominal (STC)	20 kWp
Total	60 modules
Module area	116 m²
Cell area	105 m²

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. 153 mΩ

Loss Fraction 1.5 % at STC

Serie Diode Loss

Voltage drop 0.7 V

Loss Fraction 0.2 % at STC

Module Quality Loss

Loss Fraction -0.8 %

Module mismatch losses

Loss Fraction 2.0 % at MPP

Strings Mismatch loss

Loss Fraction 0.1 %

IAM loss factor

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

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

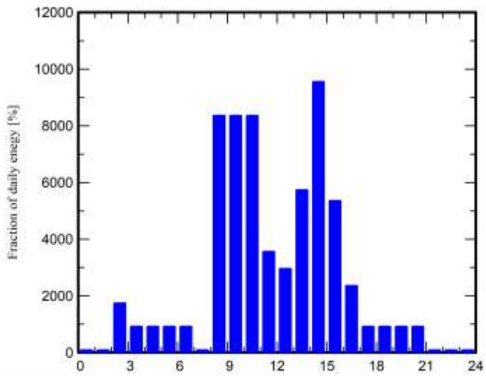
Detailed User's needs

Daily household consumers, Constant over the year, average = 64 kWh/day

Annual values

	Number	Power	Use	Energy
		W	Hour/day	Wh/day
Lamps (LED or fluo)	28	30W/lamp	9.0	7560
TV / PC / Mobile	11	150W/app	9.0	14850
Domestic appliances	2	1200W/app	2.0	4800
Fridge / Deep-freeze	1		24	151
Autres	16		24	1920
Climatiseurs	5	1200W tot	5.0	30000
Imprimantes	4	300W tot	4.0	4800
Stand-by consumers			24.0	240
Total daily energy				64321Wh/day

Hourly distribution

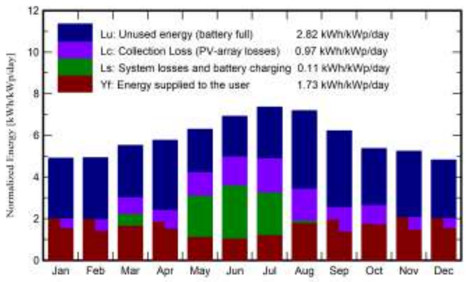


Main results

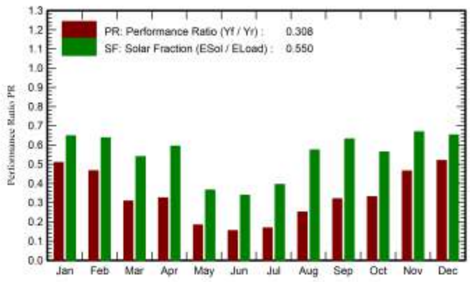
System Production

Available Energy	34047 kWh/year	Specific production	1669 kWh/kWp/year
Used Energy	12909 kWh/year	Performance Ratio PR	30.80 %
Excess (unused)	20984 kWh/year	Solar Fraction SF	54.98 %
Loss of Load		**Battery aging (State of Wear)**	
Time Fraction	69.2 %	Cycles SOW	81.0 %
Missing Energy	10568 kWh/year	Static SOW	80.0 %
		Battery lifetime	5.0 years

Normalized productions (per installed kWp)



Performance Ratio PR



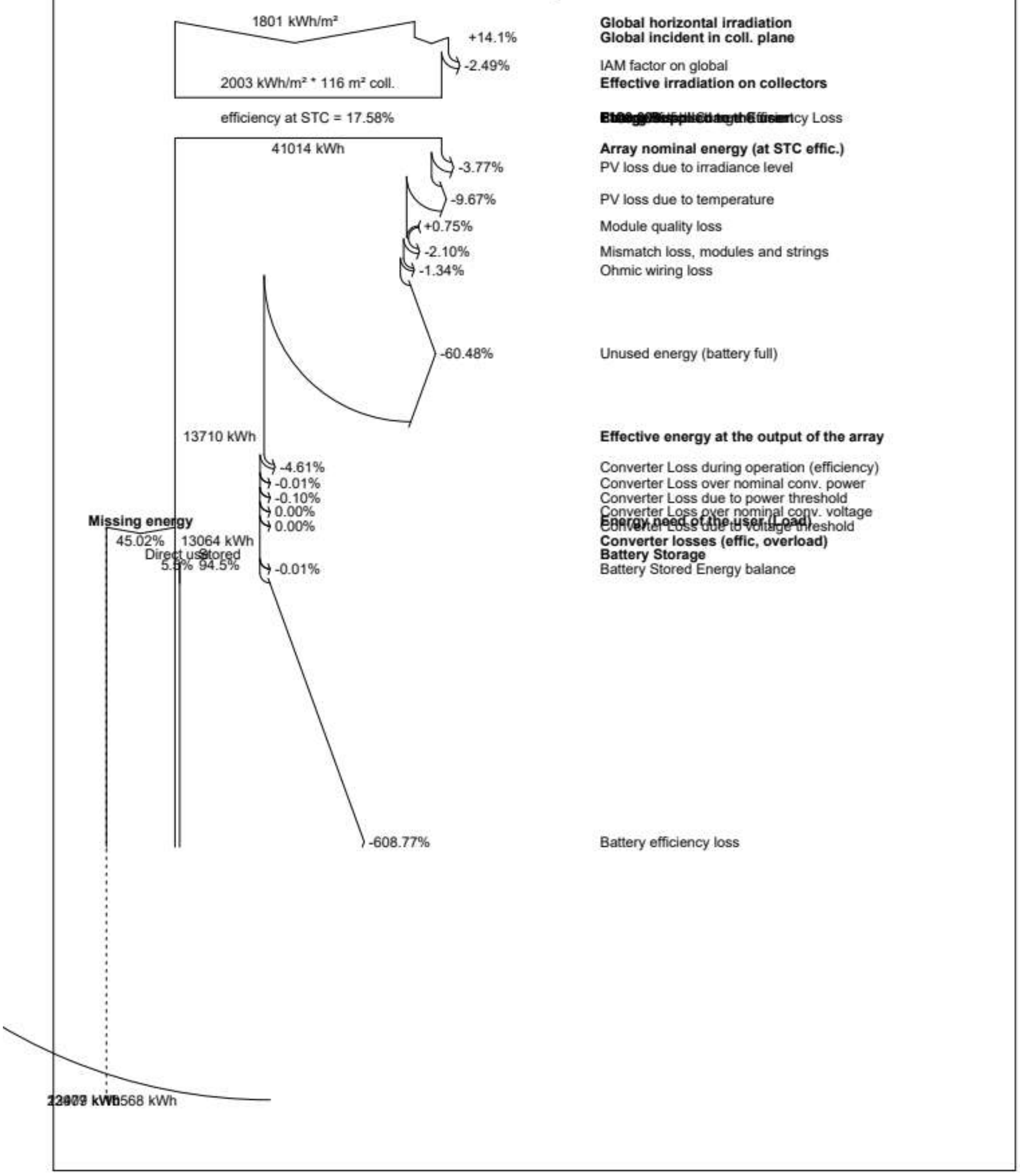
Balances and main results

	GlobHor	GlobEff	E_Avail	EUnused	E_Miss	E_User	E_Load	SolFrac
	kWh/m²	kWh/m²	kWh	kWh	kWh	kWh	kWh	ratio
January	77.7	122.1	2224	1811	701	1293	1994	0.648
February	87.2	118.1	2116	1663	653	1148	1801	0.637
March	139.5	167.0	2919	1559	918	1076	1994	0.539
April	163.6	168.3	2926	2031	783	1147	1930	0.594
May	204.2	189.3	3181	1285	1264	730	1994	0.366
June	228.2	201.2	3276	1157	1277	653	1930	0.338
July	245.1	221.4	3528	1543	1208	786	1994	0.394
August	215.7	217.0	3515	2350	849	1145	1994	0.574
September	159.4	182.1	3053	2226	711	1219	1930	0.631
October	122.7	163.0	2762	1699	871	1123	1994	0.563
November	86.2	133.4	2372	1913	640	1290	1930	0.668
December	71.6	120.3	2175	1745	693	1301	1994	0.653
Year	1801.1	2003.4	34047	20984	10568	12909	23477	0.550

Legends

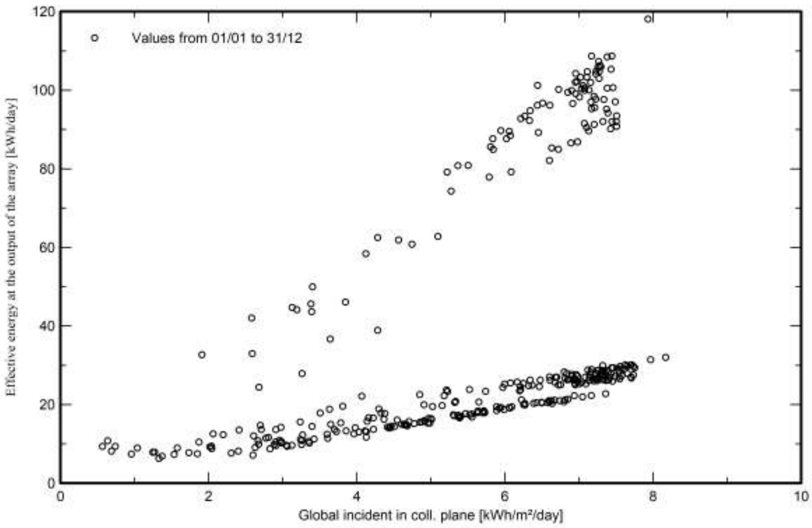
GlobHor	Global horizontal irradiation	E_User	Energy supplied to the user
GlobEff	Effective Global, corr. for IAM and shadings	E_Load	Energy need of the user (Load)
E_Avail	Available Solar Energy	SolFrac	Solar fraction (EUsed / ELoad)
EUnused	Unused energy (battery full)		
E_Miss	Missing energy		

Loss diagram



Special graphs

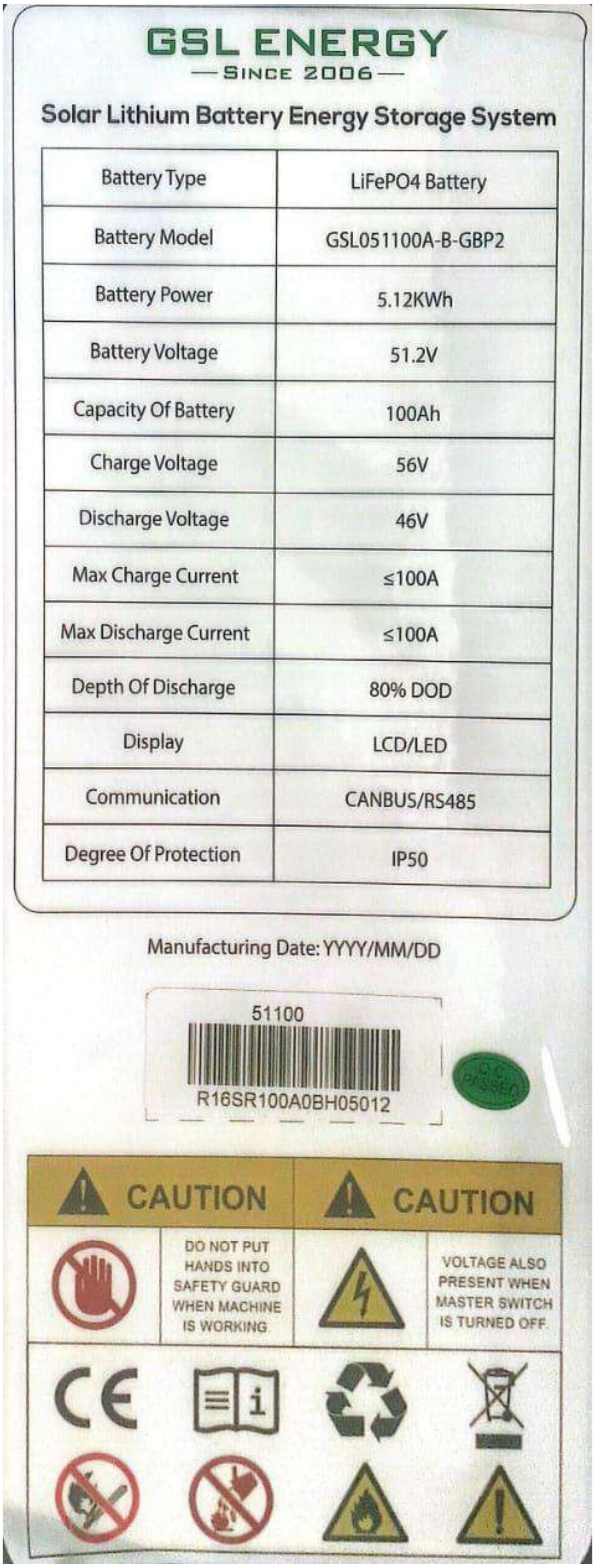
Daily Input/Output diagram



APPENDIX C

General view photo of two master-slave inverters (upper middle), AC distribution box and DC distribution box (on the left and right of the inverters), and 4 batteries.

Inverter Nameplate


GSL ENERGY
— SINCE 2006 —

Solar Lithium Battery Energy Storage System

Battery Type	LiFePO4 Battery
Battery Model	GSL051100A-B-GBP2
Battery Power	5.12KWh
Battery Voltage	51.2V
Capacity Of Battery	100Ah
Charge Voltage	56V
Discharge Voltage	46V
Max Charge Current	≤100A
Max Discharge Current	≤100A
Depth Of Discharge	80% DOD
Display	LCD/LED
Communication	CANBUS/RS485
Degree Of Protection	IP50

Manufacturing Date: YYYY/MM/DD

51100
R16SR100A0BH05012

QC PASSED

CAUTION
DO NOT PUT HANDS INTO SAFETY GUARD WHEN MACHINE IS WORKING

CAUTION
VOLTAGE ALSO PRESENT WHEN MASTER SWITCH IS TURNED OFF

CE

Battery Nameplate

Inverter Characteristics Table [Deye]

Battery Input Data					
Battery Type	Lead-acid or Li-Ion				
Battery Voltage Range (V)	40~60				
Max. Charging Current (A)	120	150	190	210	240
Max. Discharging Current (A)	120	150	190	210	240
External Temperature Sensor	Yes				
Charging Curve	3 Stages / Equalization				
Charging Strategy for Li-Ion Battery	Self-adaption to BMS				
PV String Input Data					
Max. DC Input Power (W)	6500	7800	10400	13000	15600
Rated PV Input Voltage (V)	550 (160~800)				
Start-up Voltage (V)	160				
MPPT Voltage Range (V)	200-650				
Full Load DC Voltage Range (V)	350-650				
PV Input Current (A)	13+13			26+13	
Max. PV I_{SC} (A)	17+17			34+17	
No.of MPP Trackers	2				
No.of Strings per MPP Tracker	1			2+1	
AC Output Data					
Rated AC Output and UPS Power (W)	5000	6000	8000	10000	12000
Max. AC Output Power (W)	5500	6600	8800	11000	13200
AC Output Rated Current (A)	7.6/7.2	9.1/8.7	12.1/11.6	15.2/14.5	18.2/17.4
Max. AC Current (A)	11.4/10.9	13.6/13	18.2/17.4	22.7/21.7	27.3/26.1
Max. Continuous AC Passthrough (A)	45				
Peak Power (off grid)	2 time of rated power, 10 S				
Power Factor	0.8 leading to 0.8 lagging				
Output Frequency and Voltage	50/60Hz; 3L/N/PE 220/380, 230/400Vac				
Grid Type	Three Phase				
DC injection current (mA)	THD<3% (Linear load<1.5%)				
Efficiency					
Max. Efficiency	97.60%				
Euro Efficiency	97.00%				
MPPT Efficiency	99.90%				

IFRI-SOL Solar Panel Datasheet [IFRI]

Electrical Specification

Module Type	Nominal Power Pmpp	Nominal Voltage Umpp	Nominal Current Impp	Open Circuit Voltage (Uoc)	Short Circuit Current (Isc)	Module Conversion Efficiency
IF-P330-72	330Wp	36.63V	9.01A	45.41V	9.48A	16.66%
IF-P335-72	335Wp	36.98V	9.06A	45.76V	9.56A	16.91%
IF-P340-72	340Wp	37.33V	9.11A	46.11V	9.64A	17.16%
IF-P345-72	345Wp	37.67V	9.16A	46.36V	9.72A	17.42%

Electrical Data At STC (STANDARD TEST CONDITIONS): 1000W/m² Irradiance, 25°C Cell Temperature, AM1.5g Spectrum According to EN 60904-3.
Manufacturing Tolerance (Pmax,Voc,Isc) : ±3%

NMOT

Module Type	Nominal Power Pmpp	Nominal Voltage Umpp	Nominal Current Impp	Open Circuit Voltage (Uoc)	Short Circuit Current (Isc)
IF-P330-72	266.64Wp	33.67V	7.92A	42.45V	8.39A
IF-P335-72	271.50Wp	34.07V	7.97A	42.80V	8.47A
IF-P340-72	276.36Wp	34.46V	8.02A	43.15V	8.55A
IF-P345-72	281.22Wp	34.85V	8.07A	43.50V	8.63A

Electrical Data At NMOT: 800W/m² Irradiance, 20°C Ambient Temperature, 1m/s Wind Speed.
Manufacturing Tolerance (Pmax,Voc,Isc) : ±3%

Design

Front Glass	3.2mm High Transmission Low Iron Tempered Glass, AR Coated
Encapsulant	Ethylene Vinyl Acetate (E.V.A)
Cell	5BB PERC Polycrystalline /157×157mm/ 72 Pcs
Backside	Composite Film (White, Black, ...)
Frame	35mm Anodized Aluminum (Silver/Black)

Performance at low irradiance :

Outstanding performance at low irradiance, with an average relative efficiency of 96.48% from irradiances, between 1000 W/m² and 200 W/m² (AM 1.5, 25°C).

Temperature Coefficients

Voltage Uoc (β)	-0.32%/°C
Current Isc (α)	+0.05%/°C
Output Power (γ)	-0.41%/°C
NMOT	45±2°C

Operating conditions

Maximum System Voltage	1500VDC
Maximum Series Fuse	20A
Operating Temperature Range	From -40°C to 85°C
Mechanical Load Test (Front/back)	5400Pa/2400Pa

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[IFRI] WWW.ifrisol.solar June 2021, V3

ملخص

تُعدّ الطاقة المتجددة عنصراً أساسياً في الحفاظ على استدامة كوكب الأرض، وتعتبر الطاقة الشمسية من أهم هذه المصادر لما تتميز به من نظافة ووفرة وإمكانية استغلالها في مختلف المناطق.

في هذا السياق، تهدف هذه الدراسة إلى محاكاة وتحليل نظام كهروضوئي مستقل لتوفير الطاقة الكهربائية للقسم الإداري لمديرية التوزيع لسونلغاز بميلة، مع تقييم أداء هذا النظام باستخدام برنامج PVsyst 7.1، ودراسة مدى فعاليته حيث تم إدخال مختلف البيانات الخاصة بالموقع الجغرافي، والمعطيات المناخية، ومكونات النظام مثل الألواح الشمسية، العاكس، والبطاريات.بعد ذلك تم إجراء عملية المحاكاة من أجل تقييم أداء النظام الكهروضوئي المستقل، وتحليل كمية الطاقة المنتجة على مدار اليوم والشهر والسنة.وقد أظهرت نتائج القيم المتحصل عليها من المحاكاة أنها قريبة جداً من القيم النظرية المحسوبة يدويا وكذا القيم الفعلية للمحطة الحقيقية، مما يدل على دقة النموذج المستخدم وفعالية النظام الكهروضوئي المدروس.
الكلمات المفتاحية:

الطاقات المتجددة، الطاقة الشمسية، النظام الكهروضوئي المستقل، PVsyst 7.1، المحاكاة، الأداء الطاقوي.

Abstract

Renewable energy plays a fundamental role in ensuring the sustainability of our planet. Among renewable resources, solar energy is considered one of the most important because of its cleanliness, abundance, and suitability for deployment in various regions.

In this context, the present study aims to simulate and analyze a stand-alone photovoltaic (PV) system designed to supply electrical power to the administrative department of the Sonelgaz Distribution Directorate in Mila city. The performance of this system was evaluated using PVsyst 7.1 software in order to assess its effectiveness. Various data related to the geographical location, climatic conditions, and system components, including photovoltaic panels, inverter, and batteries, were incorporated into the simulation model.

Subsequently, simulations were carried out to evaluate the performance of the stand-alone photovoltaic system and to analyze the amount of energy produced on daily, monthly, and annual bases. The simulation results showed excellent agreement with both the manually calculated theoretical values and the actual data obtained from the real installation. This close correspondence confirms the accuracy of the adopted model and demonstrates the effectiveness of the studied photovoltaic system.
Keywords : Renewable energy, solar energy, stand-alone photovoltaic system, PVsyst 7.1, simulation, energy performance.

Résumé

Les énergies renouvelables constituent un élément essentiel pour assurer la durabilité de notre planète. Parmi ces ressources, l'énergie solaire occupe une place prépondérante grâce à sa propreté, son abondance et sa possibilité d'exploitation dans diverses régions.

Dans ce contexte, cette étude vise à simuler et à analyser un système photovoltaïque autonome destiné à alimenter en énergie électrique le département administratif de la Direction de Distribution de Sonelgaz de Mila. L'évaluation des performances de ce système a été réalisée à l'aide du logiciel PVsyst 7.1 afin d'étudier son efficacité. Pour ce faire, différentes données relatives au site géographique, aux conditions climatiques ainsi qu'aux composants du système, notamment les panneaux photovoltaïques, l'onduleur et les batteries, ont été introduites dans le logiciel.

Par la suite, des simulations ont été effectuées afin d'évaluer les performances du système photovoltaïque autonome et d'analyser la quantité d'énergie produite aux échelles journalière, mensuelle et annuelle. Les résultats obtenus ont montré une très bonne concordance entre les valeurs issues de la simulation, les valeurs théoriques calculées manuellement et les données réelles de la centrale étudiée. Cette proximité confirme la précision du modèle utilisé ainsi que l'efficacité du système photovoltaïque considéré.
Mots-clés : Énergie renouvelable, énergie solaire, système photovoltaïque autonome, PVsyst 7.1, simulation, performance énergétique.