PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
Ministry of Higher Education and Scientific Research

Serial N°: ……. / 2025

Kasdi Merbah Ouargla University

Faculty of Hydrocarbons, Renewable Energies and Sciences of Earth and the Universe
Renewable Energy Department

Dissertation
To obtain the Master's degree
Option: Renewable Energy in Mechanics
Submitted by :
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-THEME-

Optimal techno-economic design of PV system comprising battery energy storage: Case study for a remote area

Defended on: 21 / 06/ 2025

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Academic Year: 2024/2025

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Abstract:

This thesis explores the optimal techno-economic design of a solar photovoltaic (PV) system with battery energy storage for remote agricultural applications in the Ouargla desert of Algeria. Remote farms face significant challenges in accessing reliable electricity due to the high cost and impracticality of grid extension and the inefficiency of diesel generators. Given the region's exceptional solar potential, the study focuses on designing a stand-alone PV-battery system capable of meeting energy demands continuously and at the lowest possible cost. A key part of the work is the development of a Python-based software tool that allows users to input technical, environmental, and economic data to simulate system performance. The algorithm uses the Loss of Power Supply Probability (LPSP) method to ensure system reliability and applies cost analysis to identify the most economically feasible configuration. Results show that for a large isolated farm, the optimal solution includes 92 solar panels, 39 batteries, and a 1000 kW inverter, with a total system cost of approximately 5.48 million DZD and a low energy cost of 0.8872 DZD/kWh. These findings were validated through comparison with HOMER Energy software, demonstrating the accuracy and reliability of the developed tool.

Keywords: Solar energy, Battery storage, Remote areas, LPSP, Python tool

Résumé : Ce mémoire porte sur la conception technico-économique optimale d'un système photovoltaïque (PV) avec stockage par batteries destiné à l'alimentation énergétique des exploitations agricoles isolées dans le désert de Ouargla, en Algérie. Ces fermes font face à d'importantes difficultés d'accès à une électricité fiable en raison du coût élevé et de l'impraticabilité de l'extension du réseau électrique ainsi que de l'inefficacité des générateurs diesel. Étant donné le fort potentiel solaire de la région, l'étude vise à concevoir un système autonome PV-batterie capable de répondre aux besoins énergétiques de manière continue et à un coût minimal. Un point central du travail est le développement d'un outil logiciel basé sur Python, permettant de saisir des données techniques, environnementales et économiques afin de simuler les performances du système. L'algorithme repose sur la méthode LPSP (Loss of Power Supply

Probability) pour garantir la fiabilité, et utilise une analyse des coûts pour identifier la configuration la plus rentable. Les résultats montrent que, pour une grande ferme isolée, la solution optimale inclut 92 panneaux solaires, 39 batteries et un onduleur de 1000 kW, pour un coût total d’environ 5,48 millions de DZD, avec un coût de l’énergie de 0,8872 DZD/kWh. Ces résultats ont été validés par une comparaison avec le logiciel HOMER Energy.

Mots-clés : Énergie solaire, Stockage batterie, Zone isolée, LPSP, Simulation Python

ملخص: يتناول هذا البحث التصميم الأمثل من الناحية التقنية والاقتصادية لنظام طاقة شمسية (كهروضوئي) مزود ببطاريات تخزين، مخصص لتوفير الكهرباء للمزارع المعزولة في صحراء ورقلة بالجزائر. تواجه هذه المناطق صعوبة في الحصول على كهرباء مستقرة بسبب ارتفاع تكلفة تمديد شبكة الكهرباء، وعدم كفاءة المولدات التي تعمل بالديزل. وبالنظر إلى الإمكانات الشمسية الكبيرة في المنطقة، ركزت الدراسة على تصميم نظام مستقل قادر على تلبية الطلب على الطاقة بشكل مستمر وبأقل تكلفة ممكنة. تم تطوير أداة برمجية باستخدام لغة بايثون تتيح للمستخدم إدخال بيانات فنية وبيئية واقتصادية لمحاكاة أداء النظام. يعتمد الخوارزم على طريقة احتمال فقدان التغذية (LPSP) لضمان موثوقية النظام، ويُجري تحليلًا اقتصاديًا لتحديد التكوين الأكثر جدوى من حيث التكلفة. أظهرت النتائج أنه لتلبية احتياجات مزرعة كبيرة معزولة، يتطلب الأمر 92 لوحة شمسية، و39 بطارية، وعاكس بقدرة 1000 كيلوواط، وبتكلفة إجمالية تقدر بحوالي 5.48 مليون دينار جزائري، مع تكلفة منخفضة لإنتاج الكهرباء تُقدر بـ 0.8872 دينار/كيلوواط ساعي. وتم التحقق من دقة النتائج من خلال مقارنة مع برنامج HOMER Energy.

الكلمات المفتاحية: الطاقة الشمسية، تخزين البطاريات، المناطق النائية، LPSP، بايثون

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Nomenclature

Symbol	Definition	Unit
Ppv	Photovoltaic power.	[W]
N_S	Number of cells.	------
N_P	Number of Panels.	------
I_{pv}	Photovoltaic current.	[A]
V_{pv}	Photovoltaic voltage.	[V]
G_t	Solar irradiance on a horizontal plane.	[W/m^2]
A_{pvg}	Surface area of the photovoltaic generator.	[m^2]
η_{pvg}	Efficiency of the photovoltaic generator.	[%]
η_r	Reference efficiency of the module.	[%]
β	Represents the module's temperature coefficient.	[%]
T_c	Cell temperature.	[C$^\circ$]
T_a	Ambient temperature.	[C$^\circ$]
N_{OCT}	Nominal operating temperature of the photovoltaic cell.	[C$^\circ$]
E_{pv}	Energy produced by the photovoltaic generator.	[wh]
SOC bat	Battery state of charge.	[wh]
DOD	Battery depth of discharge.	[%]
Nja	Number of days of backup time.	Day
η_{ond}	Inverter efficiency.	[%]
N_{bat}	Number of batteries.	------
C_i	Initial system cost.	[DA]
C_m	System maintenance cost.	[DA]
C_r	Component replacement cost.	[DA]
C_g	Overall system cost.	[DA]
$CO\&M$	Maintenance and operating cost.	[DA]

Abbreviations

Symbol	Definition
O&M	Maintenance and Operation
NOCT	Solar Cell Nominal Operating Temperature
PV	Photovoltaic
LPSP	Probability of Unsatisfied Charge
LPS	Energy deficit relative to the load.

GENERAL INTRODUCTION

Operating farms in remote areas of the Ouargla desert requires a continuous supply of electrical energy (24/7, year-round). Renewable energy systems, particularly solar power, are well-suited to meet the energy needs of cultivated areas in the heart of the Ouargla desert. Extending the electrical grid to these regions is prohibitively expensive due to installation costs, maintenance, voltage drops at high temperatures, as well as risks of sabotage and cable theft. Additionally, supplying energy to cultivated areas through generators is costly, as it depends on fuel, and transportation costs increase significantly with distance.

In this context, resorting to renewable energy sources (such as photovoltaic panels) can have a beneficial impact on electricity production in terms of cost and availability. Renewable energies are derived from sustainable natural sources. Furthermore, southern Algeria is considered one of the richest regions in the world for solar renewable energy, being located in one of the six sunniest areas globally.

This study will focus on the dimensions and cost optimization of a renewable energy system with battery storage to supply electricity to a farm in an isolated area of the Ouargla province. This thesis is structured as follows:

Chapter 1: We will explain the source of renewable energy, the principles of photovoltaic energy operation and the most important methods for analyzing and studying renewable energy systems.

Chapter 2: We will propose the mathematical model and explain the algorithm's working methodology and the methodology we will use for our calculations.

Chapter 3: Using Python on Windows, we will present the interface of our program we developed to determine the number of solar panels and storage batteries required for a predetermined load, at the lowest possible cost. We will repeat the calculations using the commercial HOMER Energy software and compare these results with those of our program.

In conclusion, we will summarize our findings and provide suggestions for future work.

CHAPTER I: Solar Energy: An In-Depth Exploration

1. Definition and Characteristics

1.1. Definition:

Solar energy is the radiant light and electromagnetic radiation (including visible light, ultraviolet, and infrared) emitted by the sun[1], harnessed and converted into usable thermal energy or electricity through a variety of technologies such as photovoltaics (directly converting photons into electrical current), concentrated solar power (using mirrors to focus sunlight for heat-driven electricity generation), and solar thermal collectors (capturing heat for water or space heating). As an abundant, inexhaustible, and fundamentally renewable resource on a human timescale, solar energy provides a sustainable and increasingly cost-effective solution to meet growing global energy demands[2]. Its utilization significantly minimizes environmental impacts compared to fossil fuels, primarily by producing no direct greenhouse gas emissions or air pollutants during operation, thereby playing a crucial role in mitigating climate change and advancing global energy security and independence.

1.2. Characteristics:

Abundance: The earth receives approximately 174 petawatts (1 petawatt = 10^{15} watts) of incoming solar radiation[3], about 30% of which is reflected back to space, while the rest is absorbed by the atmosphere, oceans, and land.

Renewable Nature: Solar energy is inexhaustible from a human perspective, as the sun is expected to continue shining for billions of years[4]. Solar energy is considered inexhaustible because it is derived from the sun, whose energy output is virtually limitless on a human timescale. The sun has been emitting energy for approximately 4.6 billion years[5], [6], and it is expected to continue doing so for another 5 billion years before it exhausts its nuclear fuel and enters its red giant phase.

Consistent Energy Source: The sun emits roughly 173,000 terawatts of energy continuously, which is more than 10,000 times the world's total energy use[5], [6]. This constant supply means that solar energy can be harnessed daily in nearly any location on Earth.

Daily and Seasonal Variability: While individual solar energy production may vary due to nighttime, weather conditions, and seasonal changes, the overall availability of solar energy remains continuous over long periods. Advances in solar technology and energy storage systems (like batteries) help mitigate these variations by storing energy for use during less sunny periods[7].

Minimal Environmental Impact: Solar energy generation has a minimal carbon footprint, as it produces no direct emissions during operation[8]. Unlike fossil fuels, which release carbon dioxide and other harmful pollutants, solar energy contributes to cleaner air and a healthier environment.

Reduced Resource Depletion: Solar panels harness energy from sunlight rather than consuming finite resources. This reduces dependence on fossil fuels, gas, and coal, which are increasingly recognized as unsustainable energy sources due to their environmental impacts.

Circular Economy Potential: Innovations in solar technology, including improvements in recycling and repurposing of solar panels, support sustainable practices within the industry. The end-of-life management and recycling of solar panels reduce waste and maximize resource recovery, making solar energy even more sustainable[9].

2. Concept of Photovoltaics: Electricity from the Sun

2.1. Definition of Solar Photovoltaics:

Solar photovoltaic (PV) energy is the technology that directly converts the energy carried by photons (particles of light) within solar radiation (or other light sources) into electrical energy (electricity)[10]. This conversion occurs at the atomic level within specially engineered materials called semiconductors, primarily silicon.

2.2. Core Principle (The Photovoltaic Effect):

When photons from sunlight strike the semiconductor material in a PV cell, they can transfer their energy to electrons in the material[11]. If the photon energy is sufficient (greater than the semiconductor's "bandgap"), it knocks an electron loose from its atomic bond, creating a free electron and a corresponding positively charged "hole." As showed in the figure 1, the structure of the PV cell (typically a p-n junction formed by doping the semiconductor) creates an internal electric field. This field acts as a one-way gate, forcing the freed electrons to move in a specific direction (towards the n-layer) and the holes to move in the opposite direction (towards the p-layer). This directional movement of electrons constitutes an electric current.

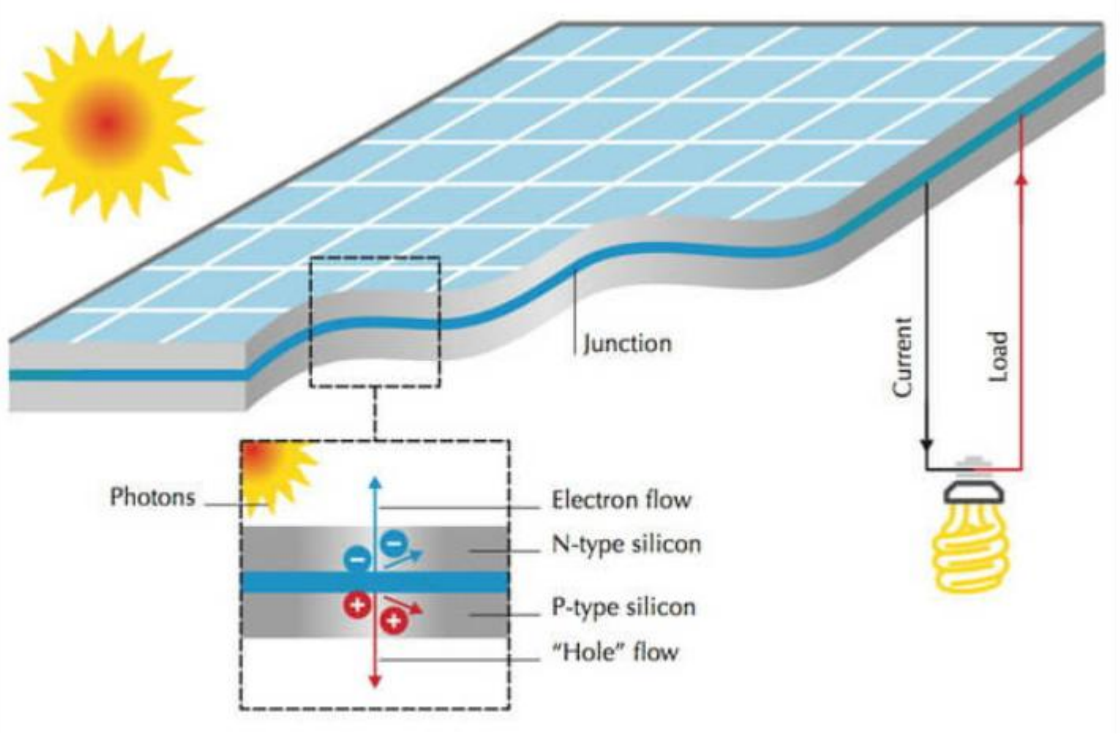

Figure 1.1 The working principle of the photovoltaic cell.

3. Components of a solar panel:

3.1. Photovoltaic Cell (or Photopile):

The photovoltaic cell (PV cell) is the fundamental semiconductor device unit where the photovoltaic effect occurs, directly converting photons (light energy) from solar radiation into electrical energy; it consists of a thin wafer or layer of semiconductor material – most commonly crystalline silicon, but also including thin-film alternatives like cadmium telluride (CdTe) or copper indium gallium selenide (CIGS) – that is deliberately engineered through a doping process to create adjacent p-type (positively charged, electron-deficient) and n-type (negatively charged, electron-rich) regions, forming a critical p-n junction which establishes a permanent internal electric field.

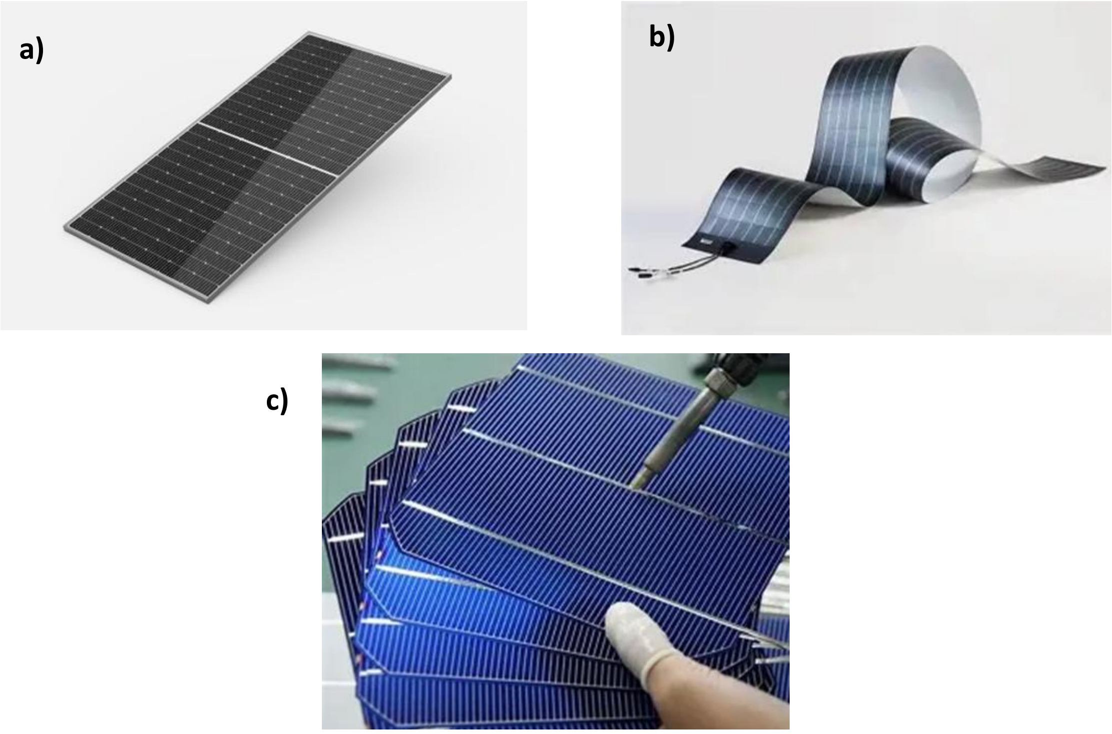

Figure 1.2 The most famous types of solar cells a) of thin-film alternatives and b) of copper indium gallium selenide (CIGS) and c) of crystalline silicon.

3.2. Photovoltaic (PV) module:

A photovoltaic (PV) module (commonly called a solar panel) is the operational unit deployed in solar energy systems, formed by electrically interconnecting multiple individual PV cells (typically 60, 72, or 96 cells in standard designs)[12] in series and/or parallel configurations using flat or ribbon-like conductors (tabbing and bus wires) to achieve the desired voltage and current output; this interconnected cell matrix is then permanently encapsulated and protected through lamination: precisely sandwiched between a high-transmission, low-iron tempered glass front sheet (providing mechanical strength, optical clarity, and weather resistance) and a multi-layered polymer back sheet (serving as an electrical insulator and moisture barrier), bonded together under heat and vacuum by sheets of ethylene-vinyl acetate (EVA) or polyolefin encapsulant that melt, flow, and cure to form a transparent, adhesive, and durable seal that mechanically stabilizes the cells, prevents moisture ingress, and protects against environmental degradation (UV radiation, thermal cycling, hail impact, abrasion); the laminated assembly is finally secured within a rigid aluminum frame (providing structural integrity, mounting points, and edge protection) featuring integrated drainage channels to prevent water pooling, while a junction box (attached to the back sheet) houses electrical terminals, bypass diodes (critical for minimizing power loss during partial shading by providing alternative current paths around shaded cells), and cabling for system integration – resulting in a robust, weatherproof, and standardized unit (as visually depicted in Figure 3) capable of decades of reliable outdoor operation on residential rooftops, commercial buildings, or utility-scale solar power plants. The main characteristics of the most important types of solar panels are summarized in Table 1.

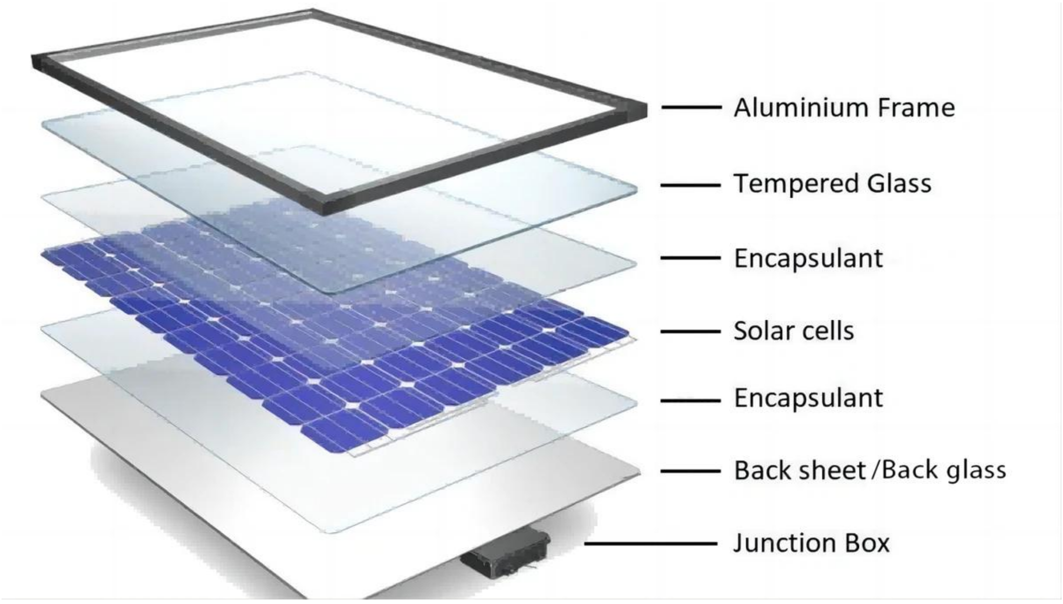

Figure 1.3 Components of a typical solar panel

During assembly it is recommended make Series Connection, to generate a higher voltage than a single cell (often needed to match battery charging Initial voltages or inverter inputs), numerous cells (typically 60, 72, or 96) are connected in series. This increases the total voltage (V_total = V_cell1 + V_cell2 + ... + V_cellN), while the current (I) remains roughly the same as the weakest cell as shwen in th figuer 4. By adding identical cells or modules in series, the string current remains the same, but the voltage increases proportionally to the number of cells (modules) in series.

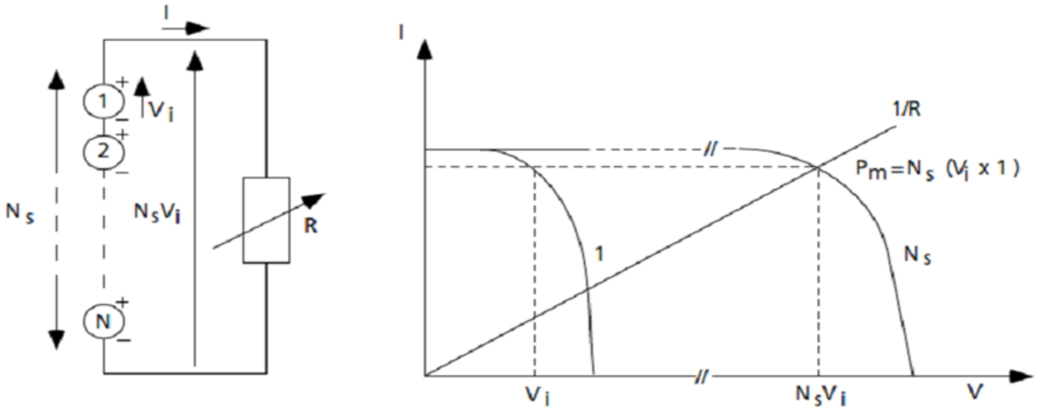

Figure 1.4 Identical cells in series

By adding identical modules in parallel, the string voltage is equal to the voltage of each module, and the current increases proportionally to the number of modules in parallel in the string as shwen in the figure 5.

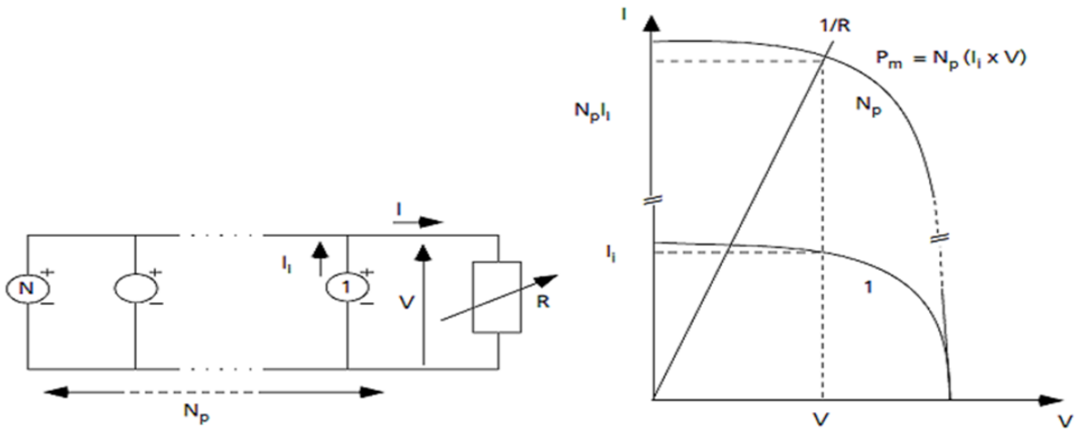

Figure 1.5 Identical cells in parallel

Table .1 table summarizing the key characteristics of the three major solar cell technologies

Characteristic	Crystalline Silicon (c-Si)	Cadmium Telluride (CdTe) (Thin-Film)	Copper Indium Gallium Selenide (CIGS) (Thin-Film)
Market Share	**Dominant** (>95% of global PV market)	**2nd most common** thin-film (~5% of global market)	**Niche player** (<2% of global market)

Thin semiconductor layer deposited on glass, metal, or flexible polymer	**Moderate-to-High** 15-19% (commercial) Lab records >23%	**Higher** Complex manufacturing and indium/gallium cost	**Lightest/Thinnest** Flexible versions enable novel applications
Thin semiconductor layer deposited on glass or flexible substrates	**Moderate** 16-19%	**Lowest** Lowest manufacturing cost due to simple deposition and low material use	**Lighter** than c-Si (glass-based) Can be flexible (on metal foil)
Rigid wafer-based cells (monocrystalline or polycrystalline)	**Highest** Monocrystalline: 20-23% Polycrystalline: 17-20%	**Moderate** Lower than historical, but higher upfront than thin-film	Heavy, rigid modules (glass-glass or glass-backsheet)
Structure	**Efficiency (Typical Module)**	**Cost ($/W)**	**Weight & Thickness**

Moderate (-0.3% to -0.4%/°C)	**Very Good**	Uniform dark appearance Flexible versions allow curved surfaces
Better heat tolerance (-0.2%/°C) Superior performance in hot climates	**Excellent** Better energy yield under diffuse light/clouds	Uniform black appearance (no gridlines) Better architectural integration
Higher loss (-0.3% to -0.5%/°C) Performance drops more in heat	Good	Standard blue/black panels with visible gridlines
Temperature Coefficient	**Low-Light Performance**	**Aesthetics**

4. Photovoltaic System

Understanding the transition from a single solar cell (Cell) to a fully integrated Photovoltaic System (PV System) is fundamental to grasping how we harness the sun's energy and transform it into usable electricity. This transition isn't just mechanical assembly; it's a complex engineering process requiring the integration of components, control systems, and infrastructure to achieve efficiency, reliability, and safety. The concept of the transition is summarized in figure 6,

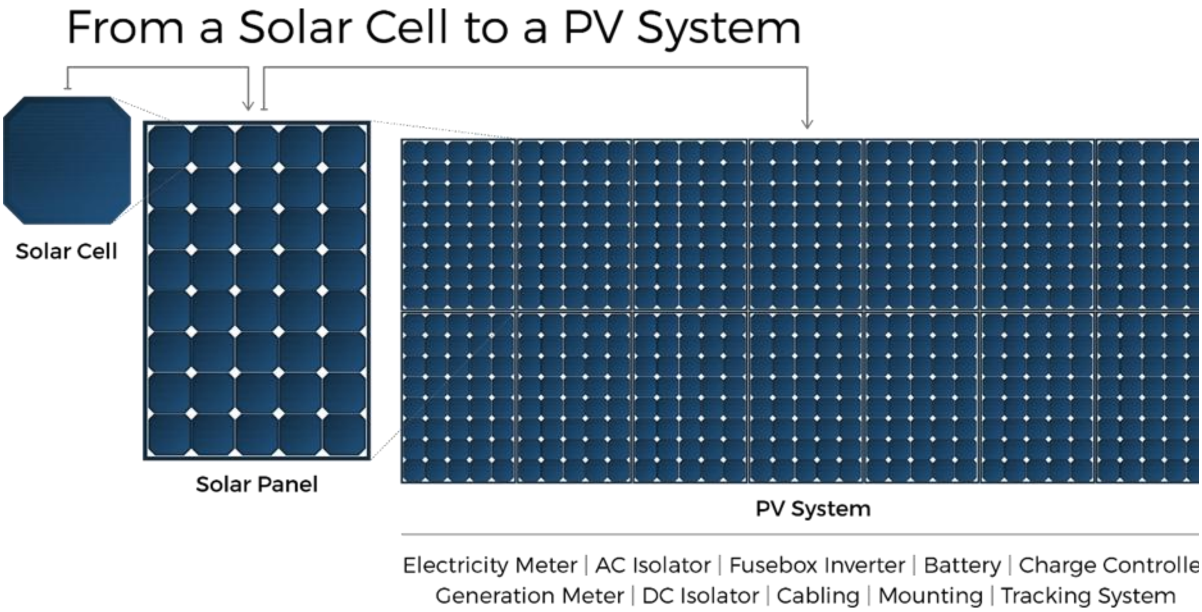

Figure 1.6 Schematic diagram of a photovoltaic system

4.1. Converters:

In a renewable energy system, converters are used to charge storage batteries and convert DC to AC [13]as shwen in the figure 7. Three types of converters are commonly found in renewable energy system: rectifiers, inverters, and choppers.

- Rectifiers: perform AC/DC conversion. In hybrid systems, they are often used to charge batteries from an AC source. These are relatively simple, inexpensive, and efficient devices.
- Inverters: convert DC to AC. They can operate independently to power AC loads.
- Choppers: the third type of converter, perform DC/DC conversion, for example, to adapt the voltage between two sources.

Figure 1.7 An illustrative explanation of the role of an inverter in a renewable energy system.

4.2. Storage Electrical Energy (Batteries):

The current preferred method of electrical energy storage is the accumulator. Whether in cell phones or cars, batteries are widely used[14]. The technology is based on the chemical concept of the battery (chemical energy is accumulated). Fundamentally, the basic element of a battery is composed of two electrodes, acting as an anode and a cathode, as well as an electrolyte in contact with the electrodes, which allows the circulation of ions, and therefore the creation of a current[15].

Among the many sectors currently being developed:

- Lead-acid batteries, commonly used to power installations that cannot withstand power outages (hybrid installations in remote sites, hospitals, etc.).
- Nickel-cadmium batteries, widely used in all electric vehicles. However, the main drawback of this process lies in the use of cadmium, which is a heavy metal.
- All processes derived from lithium batteries: lithium-ion, lithium polymer, lithium-metal-polymer, etc.

Figure 1.8 A group of batteries connected in series

5. Load

The load is the electrical equipment powered by the system. It can be DC, such as telecommunications equipment or water pumps, or AC, for domestic use[16].

Electrical loads generate electrical power. There are resistive and inductive loads. Resistive loads include incandescent light bulbs, water heaters, etc. Appliances using electrical machines are resistive and inductive loads. They are the main consumers of reactive power. DC loads can also have inductive components, but the only effects introduced by these are transient voltage and current variations during changes in system operation[17].

6. Methods for studying and sizing renewable energy systems

Sizing renewable energy systems involves various techniques that ensure a system can meet energy demands reliably and efficiently. Here’s a breakdown of the primary methods, their characteristics, and applications:

- **Resource Assessment**[18]**:** Resource assessment focuses on quantifying the raw availability of a renewable energy resource in a particular region. It involves the collection and analysis of data such as solar irradiance, wind speed and direction, biomass availability, or hydrological flow rates. This method incorporates geographic, seasonal, and temporal variability using satellite data, meteorological measurements, and ground-based sensors.

- **Production Simulation Models**[19]**:** These models simulate the performance of renewable energy systems over time using historical or synthesized weather data, coupled with technology parameters. The goal is to estimate actual energy output across various operational scenarios, including system downtime, temperature effects, and degradation.
- **Levelized Cost of Energy (LCOE)**[20]**:** LCOE represents the per-unit cost (typically per kWh) of building and operating a generating plant over an assumed financial life and duty cycle. It accounts for capital investment, operations and maintenance (O&M), fuel costs (if any), and financing.
- **Risk Assessment Methods**[21]**:** These methodologies focus on identifying and quantifying uncertainties and risks associated with renewable energy deployment, including technical failures, climatic variability, regulatory risks, and market volatility. They can include probabilistic models, Monte Carlo simulations, and scenario analysis.
- **Loss of Power Supply Probability (LPSP)**[22]**:** The Loss of Power Supply Probability (LPSP) is a quantitative reliability metric used in the design and analysis of renewable energy systems, especially standalone (off-grid) or hybrid systems. It measures the probability that the system fails to meet the energy demand at any given time, often due to the intermittent nature of renewable resources like solar and wind.

Several software tools can facilitate the mathematical optimization of renewable energy systems:

- **HOMER**: A widely used software for optimizing microgrid and hybrid system designs.

- **MATLAB/Simulink**: Allows users to implement custom optimization algorithms based on linear and non-linear programming.
- **GAMS (General Algebraic Modeling System)**: A high-level modeling system for mathematical programming problems.
- **Python Libraries**: Tools like SciPy, PuLP, and Pyomo for building and solving optimization model

Chapter II: developing an algorithm to size and optimize a renewable energy system

1. Method for sizing renewable energy system:

The renewable energy system allows for better exploitation of available renewable resources, making it more economically competitive. However, choosing the optimal configuration based on the specific site conditions, the technical data of the components, and the load consumption remains the main problem.

There are currently several methods for sizing renewable energy systems. In our study, we will use a method based on the Loss of Power Supply Probability (LPSP) load, which will be a value desired by the user. Then, among all the configurations that satisfy the LPSP, an economic analysis is chosen to determine the optimal configuration. Using LPSP for sizing renewable energy systems offers several advantages:

- **Reliability Control:** LPSP directly quantifies the system's ability to meet demand without interruptions, allowing designers to ensure an appropriate balance between reliability and cost.
- **User-Specified Thresholds:** Since LPSP is a user-defined metric, it provides flexibility in determining acceptable reliability levels. Critical applications may require ultra-low LPSP, while non-essential systems can tolerate higher values.
- **Optimized Resource Allocation:** By filtering out configurations that fail to meet the LPSP threshold, the method ensures efficient use of renewable resources, battery storage, and backup systems.
- **Economic Feasibility:** Rather than blindly oversizing components, LPSP helps refine system sizing so that the most cost-effective solution within acceptable reliability limits is selected.
- **Adaptability to Site-Specific Conditions:** LPSP integrates real-world variability in solar radiation, wind speed, and consumption patterns, making it highly adaptable across different geographic locations and energy needs.

a) **Avoids Unnecessary Oversizing:** Traditional sizing methods may lead to oversized systems for absolute reliability, driving up costs. LPSP prevents this by setting a rational trade-off between reliability and affordability.

2. Calculation of the power produced by the photovoltaic generator:

The performance of photovoltaic modules depends on several parameters, namely illumination, temperature and state of charge[23]. Using MPPT control allows maximization of the extracted power[24]. We will use a simple model of the photovoltaic generator which allows us to calculate the power produced at any time if the temperature and illumination $Gt \left(\frac{W}{m^2}\right)$ are known.

$$Ppv = \eta pvg \cdot Apvg\, Gt \tag{1}$$

With $Apvg(m^2)$ is the surface of the photovoltaic generator, and ηpvg represents the efficiency of the latter and it is given by:

$$\eta pvg = \eta r \cdot \eta pc\, [1 - \beta\, (Tc - Tc\, ref)] \tag{2}$$

With ηr is the reference efficiency of the module, ηpc is the efficiency characterizing the state of charge, the latter is equal to 1 in the case of using the MPPT control strategy. β represents the temperature coefficient which is assumed to be constant and for silicone-based photovoltaic cells β is in the range 0.004 to 0.006 (1/°C). $Tc\, ref$ is the reference temperature of the cell (°C), Tc is the temperature of the cell given by:

$$Tc = Ta + \left(\frac{NOCT - 20}{1000}\right) Gt \tag{3}$$

Ta (°C) is the ambient temperature and $NOCT$ (°C) represents the nominal operating temperature of the photovoltaic cell.

These different parameters are provided by the manufacturers for each type of photovoltaic module.

3. Mathematical Modeling of Storage:

The mathematical model of the battery's state of charge depends on the previous state, as well as the energy produced by the photovoltaic generator (Epv) and the energy required by the load (Ech). The battery state of charge (SOC) SOC_{bat} can be calculated using two scenarios.

a) First scenario:

In case $Epv(t) \geq Ec(t)$, the batteries are in the charging process. And the instantaneous storage capacity $SOCbat(t)$ $[W\text{h}]$ is given by:

$$SOC_{bat}\,(t) = SOC_{bat}\,((t-1) + (E_{pv}\,(t) + Ech\,(t))\,\eta_{ond})\,\eta c_{\text{ha}} \tag{4}$$

With :

$$\begin{cases} Epv\,(t) = Ppv\,(t)\,\Delta t \\ \qquad and \\ Ech\,(t) = Pch\,(t)\,\Delta t \end{cases}$$

$Ppv\,(t)$, $Pch\,(t)$ are respectively: the power produced by the photovoltaic generator at time t, and the power required by the load at time t. $\varDelta t$ is the simulation step ($\varDelta t$= 1h).

ηond represents the inverter efficiency and ηcha the battery charging efficiency varies from 0.65 to 0.85 depending on the charging current.

b) Second scenario

In the case $Epv\,(t)$ <$Ech\,(t)$ we will have two possibilities:

a) If $Epv\,(t) \geq Ech\,(t)/\eta ond$, the batteries are in charging situation and the storage capacity is given by:

$$SOCbat(t) = SOCbat\ (t-1) + \left(Epv(t) - \left(\frac{Ech\ (t)}{\eta ond}\right)\right)\eta_{ch} \tag{5}$$

b) If $Epv\ (t) < Ech(t)\ /\eta ond$, which corresponds to the battery discharge process which is characterized by the following relation:

$$SOCbat(t) = SOCbat\ (t-1) + \left(Epv(t) - \left(\frac{Ech\ (t)}{\eta ond}\right)\right)\frac{1}{\eta_{dec\ h}} \tag{6}$$

With ηdec h the discharge efficiency of the batteries, it is assumed equal to 1.

4. Limits of battery charge status:

For all scenarios the battery charge state must satisfy the following condition:

$$SOCbat_{min} \leq SOCbat\ (t) \leq SOCbat_{max} \tag{7}$$

With $SOCbat_{max}$, $SOCbat_{min}$ the charging limit states of storage batteries. $SOCbat_{max}$ considered as the nominal capacity of the storage system $Cbatn$ and the lower limit can be expressed by:

$$SOCbat_{min} = DOD\ Cbatn \tag{8}$$

DOD (%) represents the depth of discharge of the batteries.

5. Determination of nominal storage system capacity in [Wh]

The battery capacity in Wh depends primarily on the number of days of autonomy (Nja), the energy produced each day by renewable resources without the storage system, and the daily energy consumption by the load.

For each day j of the year, we calculate the difference in value between the energy required by the load and the energy produced by renewable generators. This determines the dynamics of the battery state of charge.

$$Ed\ (t) = Ech\ (t) - Ep\ (t) \tag{9}$$

$$Ep\ (t) = Epv\ (t) \tag{10}$$

$$Ed\ (j) = \sum_{t=1}^{24} E_d\ (t) \quad if \quad Ed\ (t) = 0 \tag{11}$$

Then for the cases where there is energy deficit $Ed\ (j) > 0$ we seek the maximum of the difference between the energy demanded and the energy produced daily over a year, to determine the nominal capacity is given as follows:

$$c_{bat_n} = \frac{Nja \cdot Max\ E_d(j)}{\eta_{dec\ h}} \tag{12}$$

The battery state of charge limits are defined by:

$$SOC_{max} = C_{bat_n} \tag{13}$$

$$SOC_{min} = DOD\ C_{bat_n} \tag{14}$$

6. Sizing the Energy Renewable System

The main objective of this sizing is to determine the optimal configuration of the photovoltaic and storage system to meet the power requirements of the load. We will first apply the Loss of Power Supply Probability (LPSP) method.

Then, based on the configurations obtained, we will use the economic approach to determine the optimal configuration.

6.1. Method Description

During operation, the following scenarios apply:

a) The power required by the load is less than the power produced by the photovoltaic generator ($Pch < Ppv$). In this case, the excess energy and the energy produced are stored in the batteries through the static converters.

b) The power required by the load is greater than the power produced by the photovoltaic generator ($Pch > Ppv$). The batteries will discharge and compensate for the energy deficit through the inverter, provided that the bottom discharge limit is not reached $[SOC]\_bat = [SOC]\_(bat\_min)$.

In case (b), if the battery energy is insufficient to meet the load's power demand at time t, this deficit is called the Loss of Power Supply (LPS), expressed as:

$$LPS\,(t) = (Pch\,(t)\,\Delta t - (Ppv\,(t)\,\Delta t + Cbat\,(t-1) - SOCbat\_min)\,\eta ond \qquad (15)$$

6.2. The LPSP Technique

LPSP is defined as the fraction of the energy deficit over that demanded by the load. It expresses the rate of unsatisfaction of the load. This probability is defined as the sum of all Loss of Power Supply (LPS) energy losses over the total energy demanded by the network during an operating period T (for us, T = 1 year) according to the following expression [25]:

$$LPSP = \frac{\sum_{t=1}^{T} LPS\,(t)}{\sum_{t=1}^{T} P_{res}\,(t)\Delta t} \qquad (16)$$

6.3. The Developed Algorithm

Based on the method described above, we developed an algorithm illustrated in Figure 9. The parameters Ppv_inf, Ppv_sup represent the lower and upper limits of the photovoltaic generator's power. $dPpv$ the power variation step for the photovoltaic generator, respectively. dt represents the simulation step, and Nja represents the number of days of autonomy.

The input data for this algorithm are the solar irradiance on an inclined plane and the average ambient temperature values for each hour of a typical day in each month of the year. The desired LPSP probability value over a year and the parameters of the various system components.

This algorithm allows us to determine the number of system components that satisfy the condition in LPS. Only economic analysis can determine the optimal size of our system.

6.4. Determining the Optimal Configuration Based on Economic Analysis

After identifying the various components (P_{pv}, N_{bat}), that meet the required production cost (LPSP), we note that the function involving these three variables is nonlinear.

We have three main types of costs for each system component:

a) Initial cost:

This relates to the cost of purchasing the system and the installation cost, which can be very significant.

$$Ci = PpvCi\_pv + NbatCi\_bat + SondCi\_ond \qquad (17)$$

With:

Ci_pv: The initial cost of the photovoltaic system [DA/W]

Ci_bat: The initial cost of the storage system [DA/Nba]

Ci_ond: The initial cost of the inverter [DA/VA]

S_ond: The apparent power of the inverter [VA]

b) The maintenance cost:

$$Cm = (PpvCi\_pv\, mpv + NbatCi\_batmbat + SondCi\_ond\, mond)\, dvsys \qquad (18)$$

mpv: Annual maintenance percentage of the photovoltaic system [%]

m_bat: Annual maintenance percentage of the storage system [%]

m_ond: Annual maintenance percentage of the inverter [%]

$d\_(v\_sys\ )$: System lifetime [Years]

c) The cost of component replacement:

Each system component has a lifespan; it must then be replaced throughout the system's operating life.

$$C_r = C_{i_{pv}} \frac{\left(dv_{sys-\,dv_{pv}}\right)}{dv_{pv}} + N_{bat} C_{i_{bat}} \frac{\left(dv_{sys-\,dv_{bat}}\ \right)}{dv_{bat}} + S_{ond} C_{i_{ond}} \frac{\left(dv_{sys-\,dv_{ond}}\ \right)}{dv_{ond}} \tag{19}$$

The overall organization chart is given on the following page:

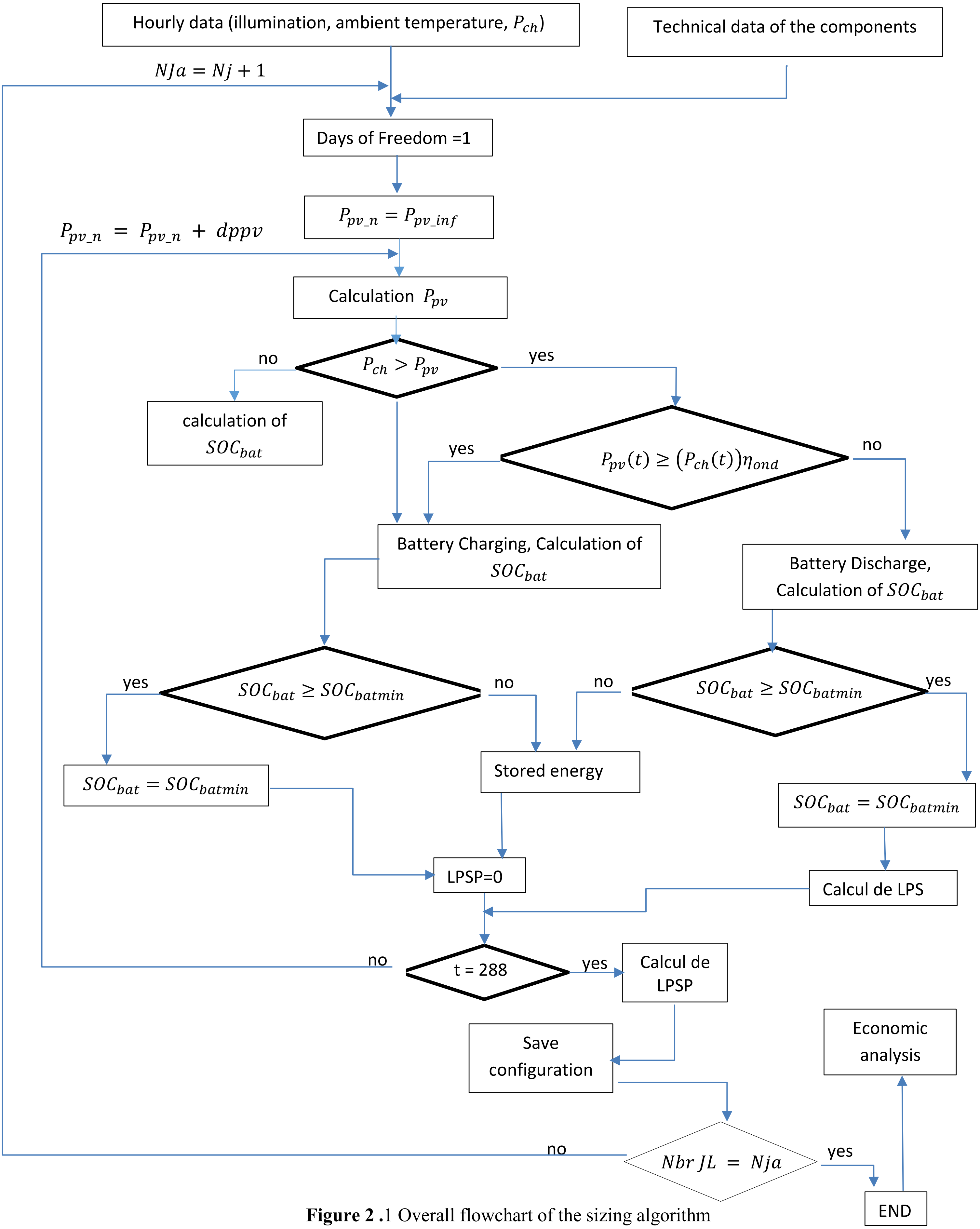

Figure 2 .1 Overall flowchart of the sizing algorithm

Chapter III: Results and comparison with program HOMER Energy results

1. Results and discussion

1.1. Presentation of our software:

The program we developed relies on the mathematical equations we explained in detail in the previous chapter. We used the Python programming language to implement the code, resulting in a fully integrated program with interactive windows. The results are presented and discussed below.

1.2. Menu principal

The main menu consists of a list of fixed inputs or data for each solar panel. It asks for the solar panel's capacity, then the solar panel's efficiency. It then asks for the battery data for both the battery voltage and the battery efficiency. It also asks for the inverter's efficiency and capacity. It then asks for the lifetime of the project, the solar panels, the batteries, and the inverter. This is necessary for maintenance calculations and cost estimation. At the bottom of the window, we find an icon. After clicking on it, we move to the next step or window to complete entering the required data, as shown in the following figure.

تصميم نظام الطاقة الشمسية

قدرة اللوح الشمسي / Panel Power (W):
كفاءة اللوح الشمسي / Panel Efficiency (%):
سعة البطارية / Battery Capacity (Ah):
جهد البطارية / Battery Voltage (V):
كفاءة البطارية / Battery Efficiency (%):
كفاءة العاكس / Inverter Efficiency (%):
عمر المشروع / Project Lifetime (years):
عمر الألواح / Panel Lifetime (years):
عمر البطاريات / Battery Lifetime (years):
عمر العاكس / Inverter Lifetime (years):
قدرة العاكس الواحد / Inverter Capacity (kW):

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Figure 3.1 First window details

as shown in the figure 11, after clicking the Next button, a window will appear to download each of the solar radiation file data, the temperature file, and the electrical load file. For each required file, there is a download button. After clicking it, it asks for the path to the file that should be retrieved. The file must have an Excel extension and contain 12 columns representing the number of months and 24 lines representing the number of hours per day. We relied on the average hourly consumption for a month for each of the solar radiation, temperature, and electrical load in order to simplify and reduce the calculation time. We also added instructions in case the Excel file that is supposed to be retrieved does not meet the condition of 12 columns and 24 lines, the file download will be rejected and a window will appear with an error message. All required files must be uploaded as shown in the figure 12.

ملف الإشعاع الشمسي / Solar Radiation File (24x12): لم يتم التحميل

ملف الحرارة / Temperature File (24x12): لم يتم التحميل

ملف الحمل الكهربائي / Load File (24x12): لم يتم التحميل

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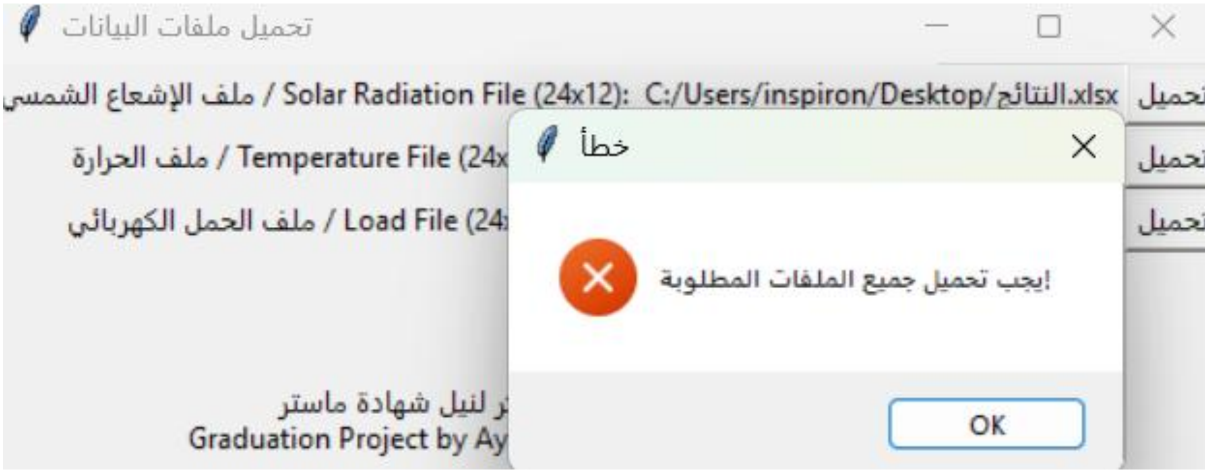
Figure 3.2 Data upload window details



ملف الإشعاع الشمسي / Solar Radiation File (24x12): C:/Users/inspiron/Desktop/النتائج.xlsx

يجب تحميل جميع الملفات المطلوبة!

Figure 3.3 How to notify in case of data upload error

After clicking on the next button, a window appears asking us to specify the cost data for each of the solar panel price, the battery price, and the inverter price. It also asks to specify the installation cost, and we consider it the same as the cost of replacing each of the solar panel, the battery, and the inverter, as shown in the figure.13 After that, a calculation icon appears at the bottom of the window. After clicking on it, the program begins to calculate.

إدخال بيانات التكلفة

سعر اللوح الشمسي / Panel Price (per unit) - DZD:
سعر البطارية / Battery Price (per unit) - DZD:
سعر العاكس / Inverter Price - DZD:
تكلفة تركيب/استبدال لوح شمسي / Panel Installation & Replacement - DZD:
تكلفة تركيب/استبدال بطارية / Battery Installation & Replacement - DZD:
تكلفة تركيب/استبدال عاكس / Inverter Installation & Replacement - DZD:

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Figure 3.4 Cost data entry window

2. Data entry and application

After running and executing the code we wrote in Visual Studio Code, an interactive window will appear asking us to enter data for the components we will rely on to provide the energy needed for the required load. We used actual data for components available in stores in Ouargla and also obtained a price list for each component required in our renewable energy system. The data used in the calculations is summarized in the table2 .

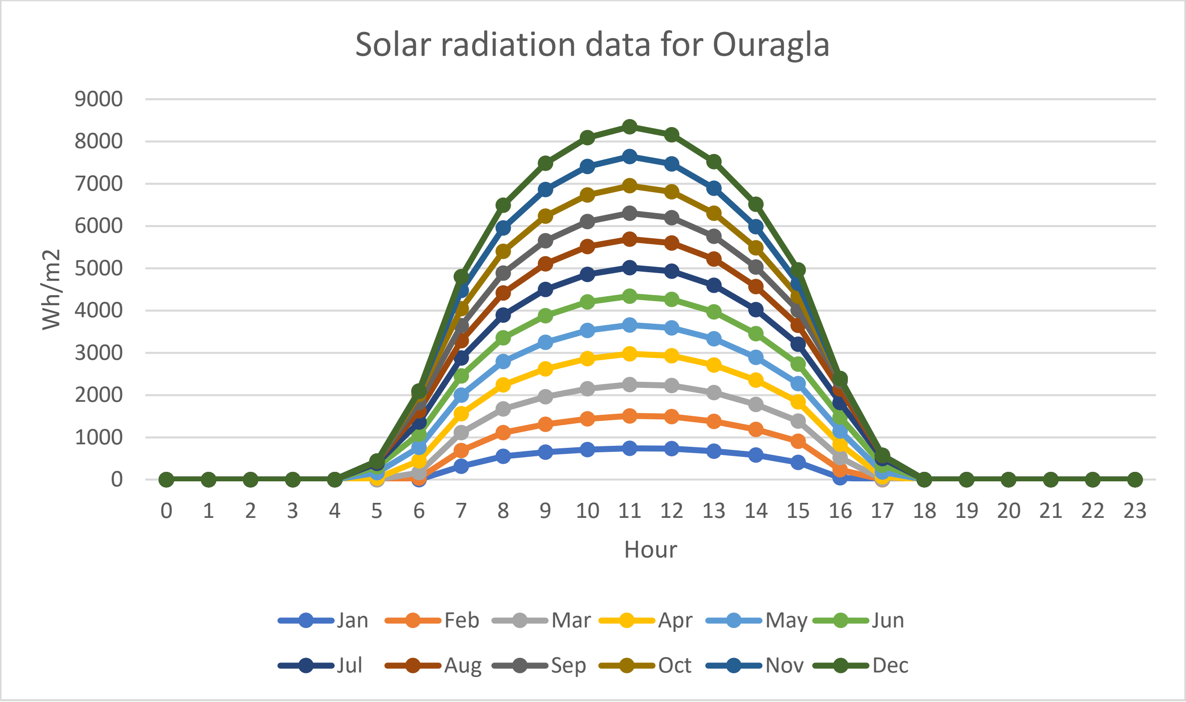
Table2. Required data for components

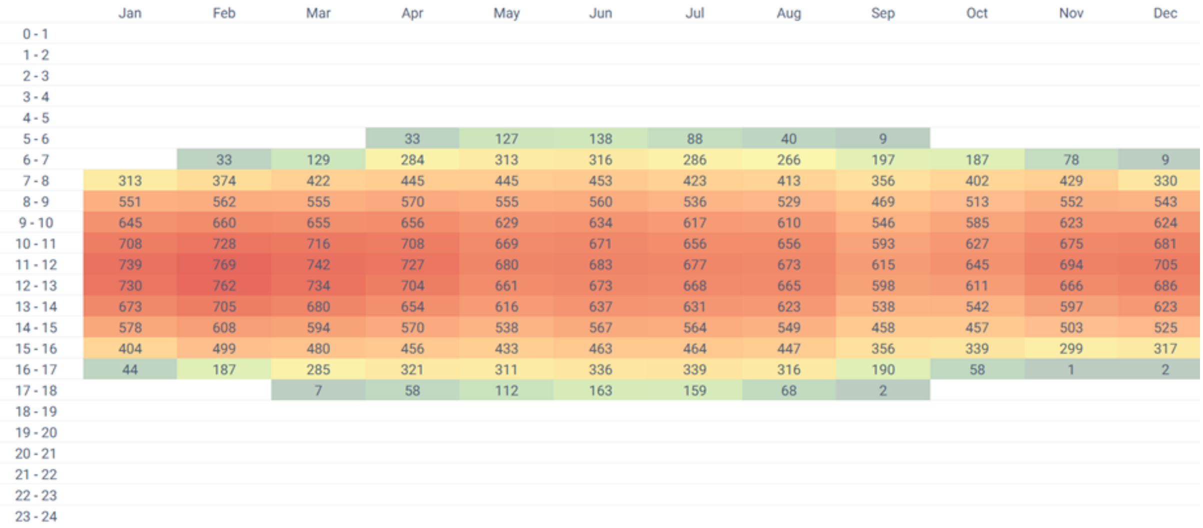
Solar panel, battery and inverter data	
Panel Power	400 (W)
Panel Efficiency	20 (%)
Battery Capacity	200 (Ah)
Battery Voltage	12 (V)
Battery Efficiency	90 (%)
Inverter Efficiency	93 (%)
Inverter Capacity	3 (kW)
Project age data	
Project Lifetime	20 (years)
Panel Lifetime	10 (years)
Battery Lifetime	5 (years)
Inverter Lifetime	10 (years)
Component and maintenance prices	
Panel Price	25000 DZD
Battery Price (per unit) -	45000 DZD
Inverter Price -	60000 DZD
Panel Installation & Replacement -	5000 DZD
Battery Installation & Replacement -	5000 DZD
Inverter Installation & Replacement -	5000 DZD

The necessary data also includes solar radiation, ambient temperature, and load. The solar radiation data for Ouargla is shown in the figure 14 and as are shown in the figure15 the temperature data. Then, the load data is shown in the figure 16. As shown in all figures, the data is shown as an average of hours over a month, so the average of one hour over a month is calculated. This way, we obtain data for 24 hours over a month and a year. We deliberately summarized the data to reduce calculations. Regarding the load data, we estimated the estimated energy consumption of a large farm located in an isolated area in the Ouargla desert.

After entering all the required data correctly and executing the code, the results details appear to us in the form of an invoice as shown in Figure 17. The number of required components was determined and it was found that to make the system completely dependent on renewable energy work independently, 92 solar panels, 39 batteries and an inverter with a capacity of 1000 kilowatts must be provided.

The results, as shown in Figure 17, also show details of the costs of both the initial installation and maintenance of all system components. The total cost of the initial installation was estimated at 132,000 DZD, while the replacement costs of components that had expired before the end of the total system lifespan were estimated at 344,000 DZD. Thus, the total cost of the project is estimated at 5,476,000 DZD, and the cost of producing one kilowatt-hour is 0.8872 DZD. This cost is considered low and suitable for producing clean electricity at a low cost.





	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6				33	127	138	88	40	9			
6 - 7		33	129	284	313	316	286	266	197	187	78	9
7 - 8	313	374	422	445	445	453	423	413	356	402	429	330
8 - 9	551	562	555	570	555	560	536	529	469	513	552	543
9 - 10	645	660	655	656	629	634	617	610	546	585	623	624
10 - 11	708	728	716	708	669	671	656	656	593	627	675	681
11 - 12	739	769	742	727	680	683	677	673	615	645	694	705
12 - 13	730	762	734	704	661	673	668	665	598	611	666	686
13 - 14	673	705	680	654	616	637	631	623	538	542	597	623
14 - 15	578	608	594	570	538	567	564	549	458	457	503	525
15 - 16	404	499	480	456	433	463	464	447	356	339	299	317
16 - 17	44	187	285	321	311	336	339	316	190	58	1	2
17 - 18			7	58	112	163	159	68	2			
18 - 19												
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												

Figure 3.5 Solar radiation data for Ouargla

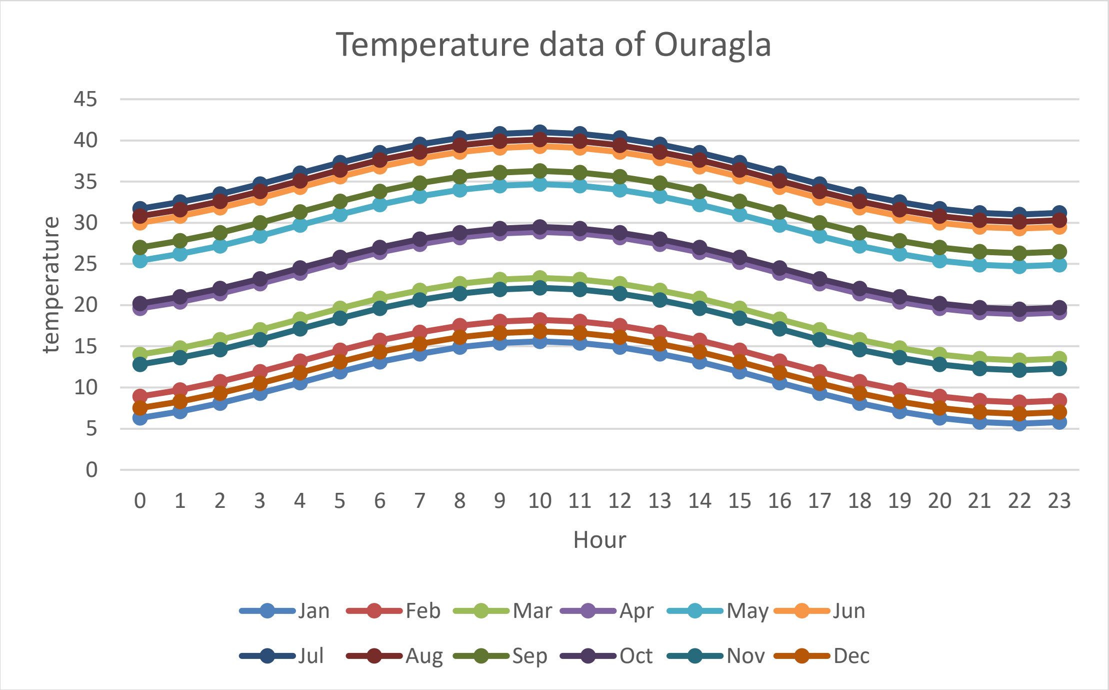


Figure 3.6 Temperature distribution data for Ouargla

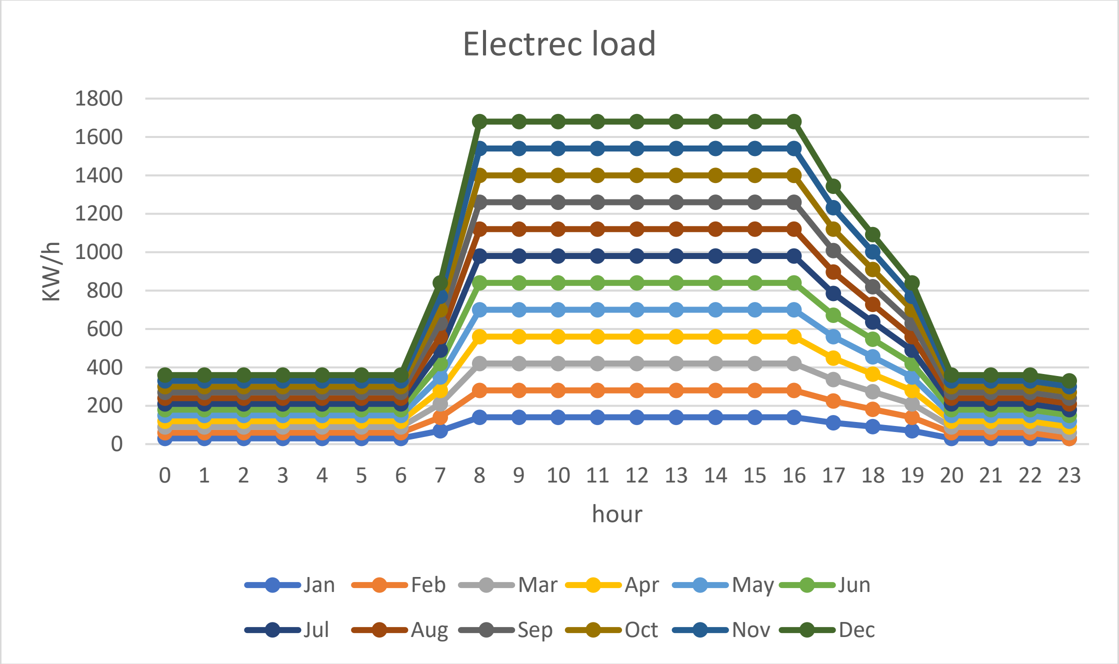
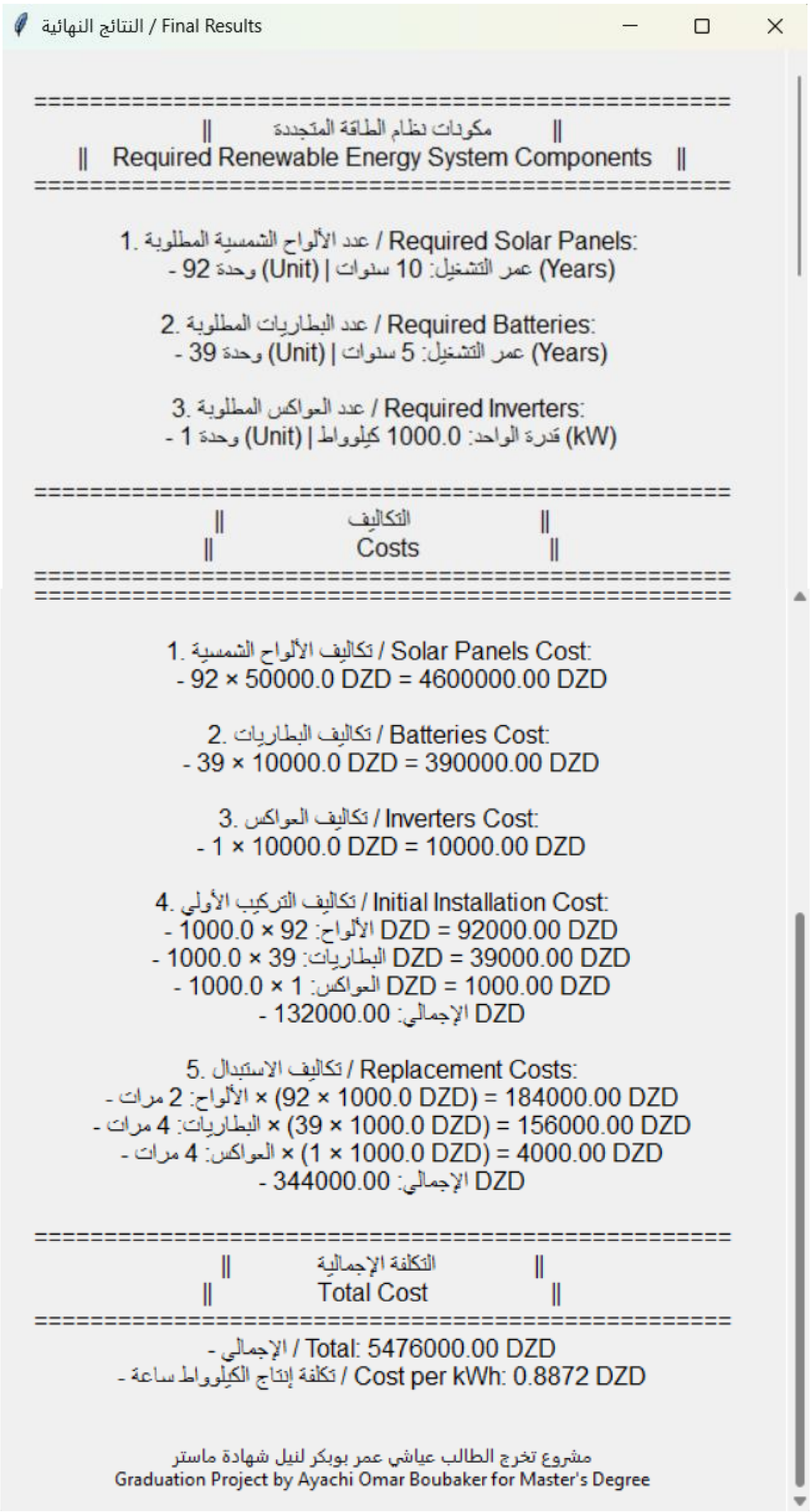


Figure 3.7 Data on the required load for a typical farm



```
========================================================
||          مكونات نظام الطاقة المتجددة          ||
||   Required Renewable Energy System Components   ||
========================================================

1. عدد الألواح الشمسية المطلوبة / Required Solar Panels:
- 92 وحدة (Unit) | عمر التشغيل: 10 سنوات (Years)

2. عدد البطاريات المطلوبة / Required Batteries:
- 39 وحدة (Unit) | عمر التشغيل: 5 سنوات (Years)

3. عدد العواكس المطلوبة / Required Inverters:
- 1 وحدة (Unit) | قدرة الواحد: 1000.0 كيلوواط (kW)

========================================================
||                 التكاليف                 ||
||                  Costs                  ||
========================================================
========================================================

1. تكاليف الألواح الشمسية / Solar Panels Cost:
- 92 × 50000.0 DZD = 4600000.00 DZD

2. تكاليف البطاريات / Batteries Cost:
- 39 × 10000.0 DZD = 390000.00 DZD

3. تكاليف العواكس / Inverters Cost:
- 1 × 10000.0 DZD = 10000.00 DZD

4. تكاليف التركيب الأولي / Initial Installation Cost:
- الألواح: 92 × 1000.0 DZD = 92000.00 DZD
- البطاريات: 39 × 1000.0 DZD = 39000.00 DZD
- العواكس: 1 × 1000.0 DZD = 1000.00 DZD
- الإجمالي: 132000.00 DZD

5. تكاليف الاستبدال / Replacement Costs:
- الألواح: 2 مرات × (92 × 1000.0 DZD) = 184000.00 DZD
- البطاريات: 4 مرات × (39 × 1000.0 DZD) = 156000.00 DZD
- العواكس: 4 مرات × (1 × 1000.0 DZD) = 4000.00 DZD
- الإجمالي: 344000.00 DZD

========================================================
||             التكلفة الإجمالية             ||
||               Total Cost               ||
========================================================
- الإجمالي / Total: 5476000.00 DZD
- تكلفة إنتاج الكيلوواط ساعة / Cost per kWh: 0.8872 DZD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```

Figure 3.8 Final results in invoice form

3. Comparison with program HOMER Energy results

HOMER energy modeling software is a powerful tool for designing and analyzing renewable energy systems that incorporate a mix of conventional generators, cogeneration, wind turbines, solar photovoltaics, hydropower, batteries, fuel cells, hydropower, biomass, and other inputs. For one or more grid-connected or stand-alone installations, HOMER helps determine how variable resources, such as wind and solar, can be optimally integrated into renewable energy systems. Engineers use HOMER to run simulations of different energy systems, compare the results, and obtain a realistic projection of their capital and operating expenses. HOMER determines the economics of a renewable energy system, optimizes system design, and allows users to truly understand how renewable systems operate. [30]

This software is considered one of the most powerful in the field of renewable energy power system design worldwide, so a comparison of the results obtained by our program is provided. Homer allowed us to evaluate the relative performance of our program and our study.

Below we explain the steps to assemble our renewable energy system in HOMER and perform the required calculations.

In the first step, the study site is selected, as shown in the figure 19. This is essential for determining the required data for the region. The figures 20 and 21 shows the data for the Ouargla region for both temperature and solar radiation, obtained from the NASA website.

In the second step, we enter the required pregnancy data so that the pregnancy data is loaded by calling a file from the computer that we prepared previously. After that, the Homer program analyzes and summarizes the data, and accordingly, the results of the distribution of pregnancy data can be displayed in different forms, as shown in the figure 22.

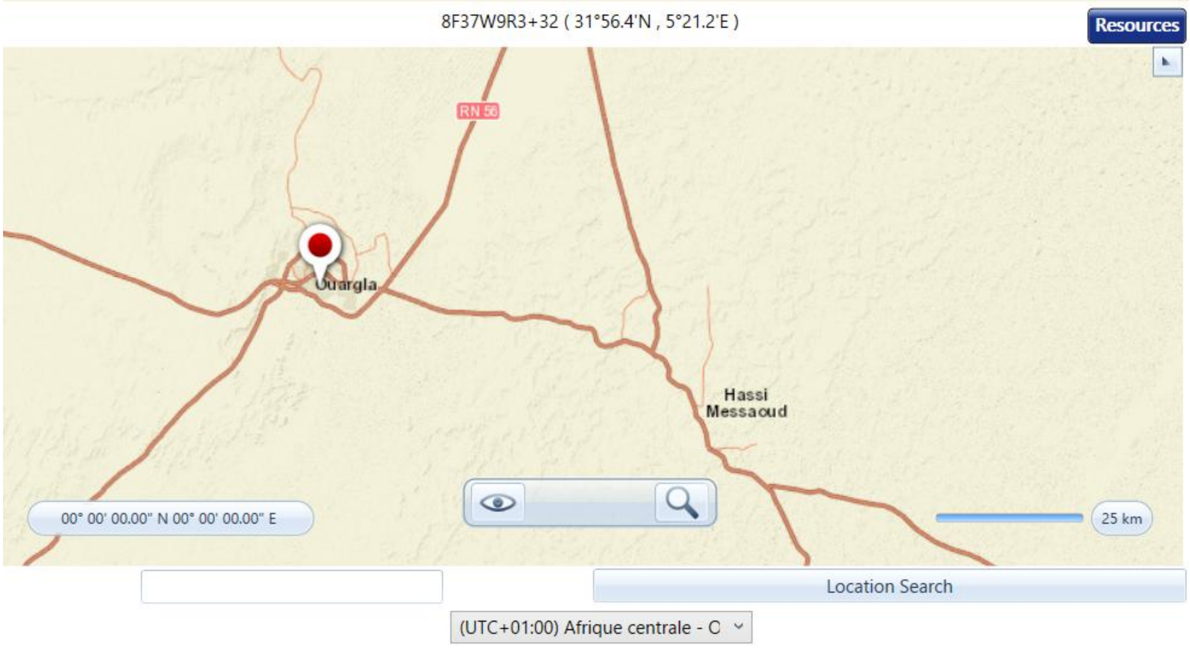
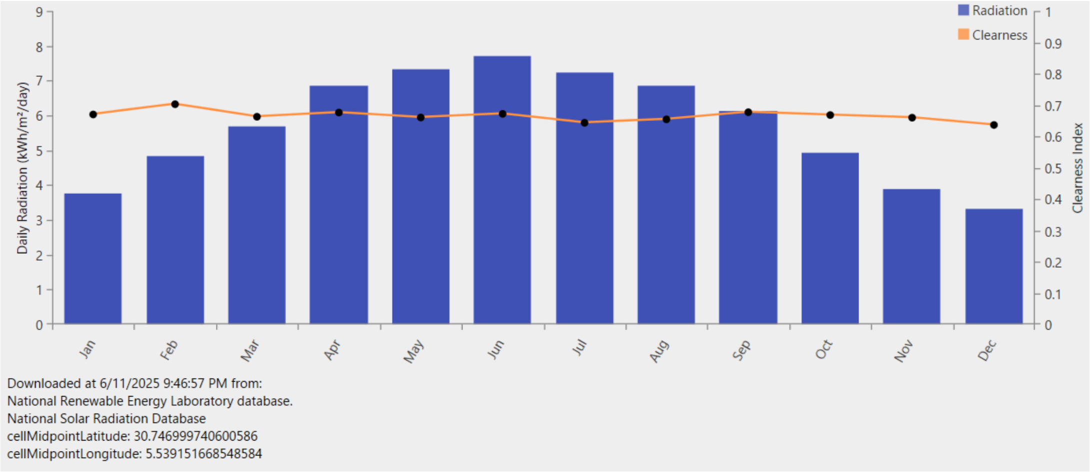
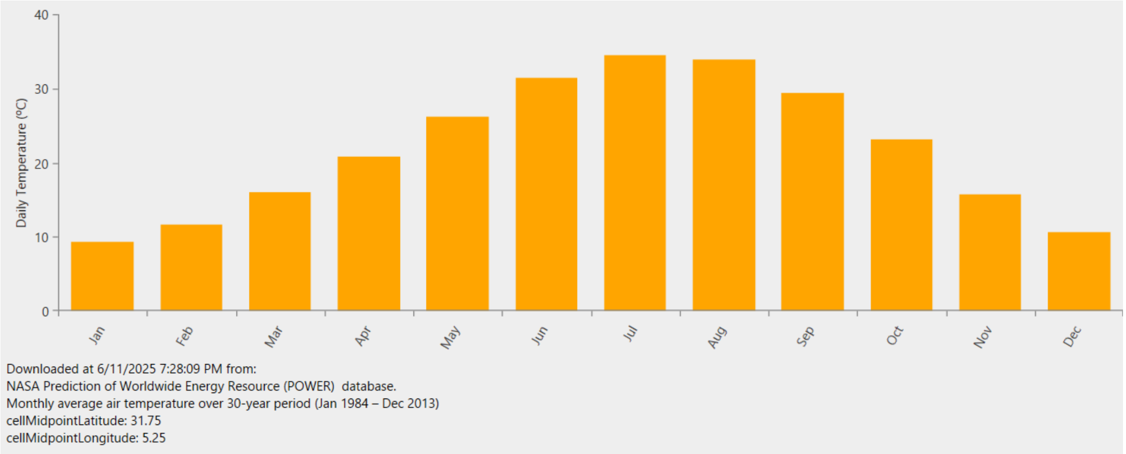


Figure 3.9 Choosing a study site



Downloaded at 6/11/2025 9:46:57 PM from:
National Renewable Energy Laboratory database.
National Solar Radiation Database
cellMidpointLatitude: 30.746999740600586
cellMidpointLongitude: 5.539151668548584

Figure 3.10 Solar radiation data for Ouargla from NASA



Downloaded at 6/11/2025 7:28:09 PM from:
NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly average air temperature over 30-year period (Jan 1984 – Dec 2013)
cellMidpointLatitude: 31.75
cellMidpointLongitude: 5.25

Figure 3.11 Temperature distribution data for Ouargla from NASA

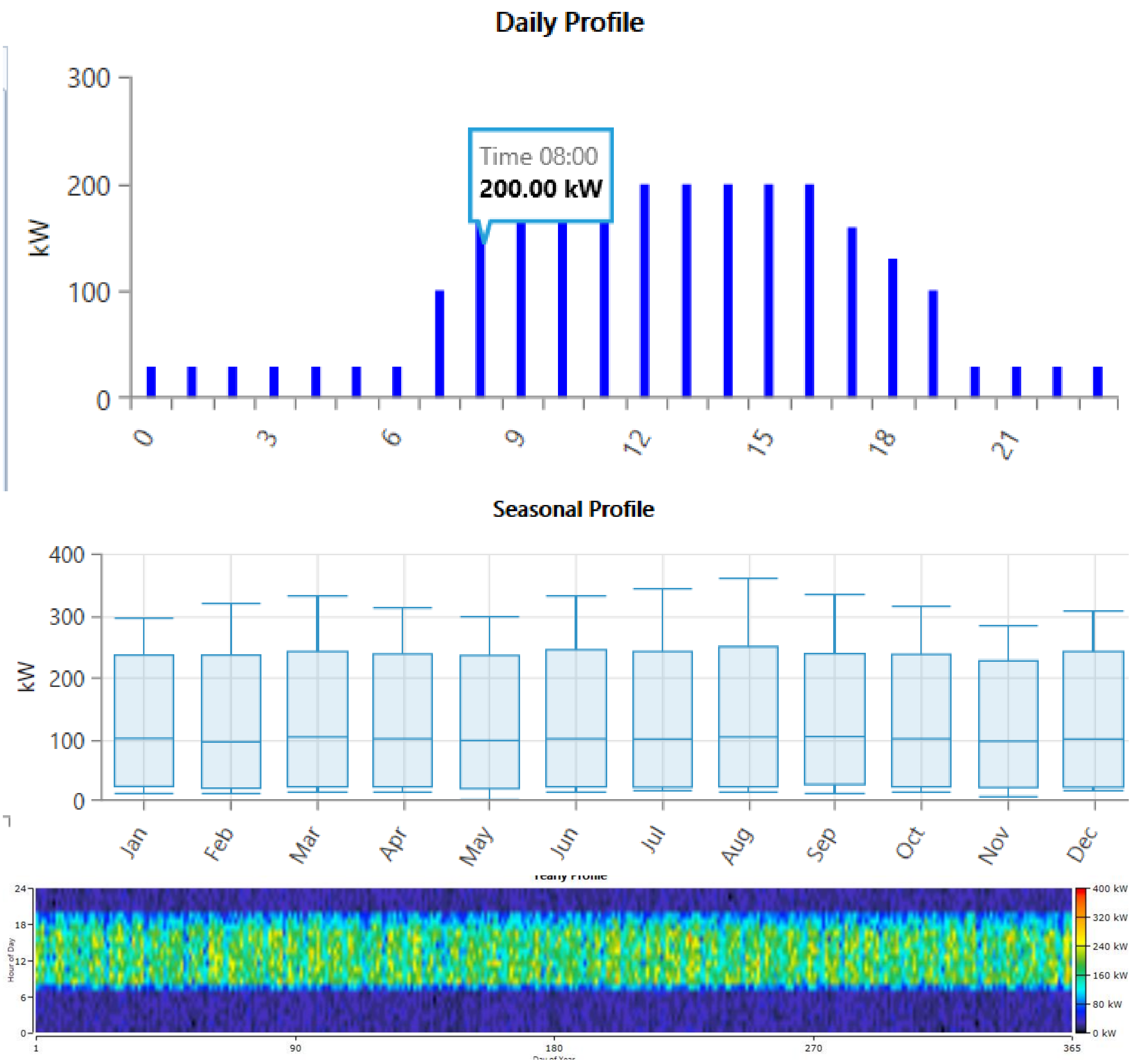


Figure 3.12 Load distribution data in different forms

In the third step, the method of connecting the system components in HOMER is engineered so that the solar panels and batteries are connected via connecting wires in the direct current part as shown in the figure 23, and then via the inverter the current is converted into alternating current where the connecting wires are connected to the load.

In the fourth step, some cost data and other component inputs are determined and entered in accordance with the data in the table above.

The results are summarized as shown in the figure 24, where it was found that the total cost of the project is 5.36M DA and the maintenance cost is 235660 DA and the cost of producing a kilowatt-hour of energy is 0.759 DA.

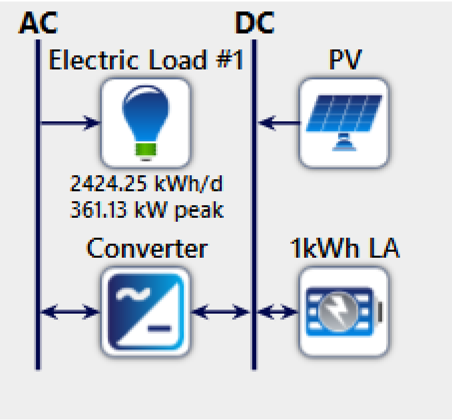
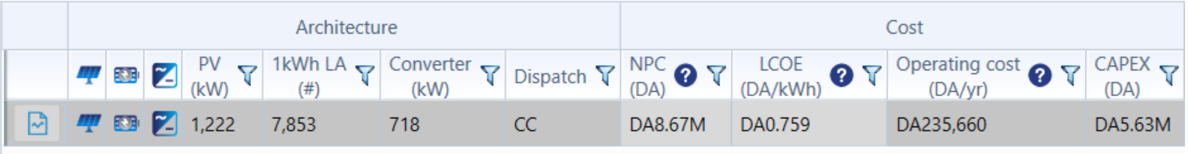


Figure 3.13 installation configuration before sizing



	Architecture							Cost			
				PV (kW)	1kWh LA (#)	Converter (kW)	Dispatch	NPC (DA)	LCOE (DA/kWh)	Operating cost (DA/yr)	CAPEX (DA)
				1,222	7,853	718	CC	DA8.67M	DA0.759	DA235,660	DA5.63M

Figure 3.14 Final results obtained from Homer

By comparing the results obtained from our program with the results of Homer, it can be noted that the results are close, and as is known, Homer's results are reliable and can be relied upon. This also confirms that the mathematical model and algorithm that we developed also show reliable and can be relied upon.

General summary

This study clearly demonstrates that a carefully sized and optimized solar photovoltaic (PV) system, integrated with battery energy storage, can serve as a reliable and economically viable solution for supplying electricity to remote and off-grid agricultural areas in the Ouargla desert of southern Algeria. The harsh desert environment, combined with the impracticality of extending the national electrical grid and the high cost and inefficiency of diesel generators, makes the deployment of standalone renewable energy systems not only desirable but essential for sustainable rural development.

By harnessing the abundant solar irradiance available in the region — one of the sunniest areas in the world — and by employing advanced modeling and simulation techniques, the study ensures that energy demands can be met around the clock (24/7), throughout the year, even during periods of low solar radiation. The inclusion of a battery storage system enhances the system's resilience and enables energy availability during nighttime and cloudy conditions, thereby addressing the intermittent nature of solar power.

A significant contribution of this work is the development of a custom Python-based software tool designed specifically for the sizing and economic assessment of PV-battery systems. The tool incorporates mathematical models for solar energy production, battery behavior (charging/discharging and state of charge), load requirements, and economic cost estimation (including initial, maintenance, and replacement costs). It also introduces a probabilistic reliability metric — Loss of Power Supply Probability (LPSP) — to ensure that the proposed configurations meet reliability standards acceptable for critical applications such as agricultural operations.

The developed tool allows users to input real hourly environmental and load data, enhancing its adaptability and relevance to different sites and usage scenarios. Its interactive design, coupled with data validation mechanisms, ensures user-friendliness and robustness. The sizing algorithm iteratively tests possible system configurations, filters those meeting the LPSP threshold, and then selects the optimal solution based on the lowest total cost over the system's lifetime.

The effectiveness and credibility of the developed tool were confirmed by benchmarking it against HOMER Energy a globally recognized software for hybrid renewable energy system design. The results from both approaches were remarkably close in terms of optimal system size, reliability, and cost indicators. This close agreement not only validates the mathematical modeling but also proves that the in-house tool can offer a competitive, cost-effective alternative to expensive commercial solutions.

In summary, this work contributes significantly to the field of renewable energy system design by offering:

- A proven method for optimal techno-economic sizing of standalone PV-battery systems.
- A practical, adaptable software tool based on open-source technologies.
- A pathway for farmers, engineers, and policymakers to promote energy independence in remote and rural regions.

The approach can be extended beyond agriculture, applying to remote clinics, schools, and communities lacking grid access. With slight modifications, it can also be tailored to hybrid systems involving wind turbines or diesel backup. Future work may focus on enhancing the tool's capabilities by integrating weather forecast data, machine learning for load prediction, or even real-time system monitoring and control via IoT platforms.

Bibliographic references

[1] L. Wald, “Solar radiation energy (fundamentals),” *Encyclopedia of Life Support System (EOLSS), Eolss Publishers, Oxford*, pp. 44–99, 2009.

[2] H. Scheer, *The solar economy: Renewable energy for a sustainable global future*. Routledge, 2013.

[3] N. S. Lewis, “Powering the planet,” *MRS Bull*, vol. 32, no. 10, pp. 808–820, 2007.

[4] F. Hsu, “Harnessing the Sun: Embarking on Humanity’s Next Giant Leap,” *Online Journal of Space Communication*, vol. 9, no. 16, p. 2, 2021.

[5] T. Tanabe, “Energy and History of the Earth,” in *Radiation: An Energy Carrier*, Springer, 2022, pp. 141–145.

[6] E. Hossain, *The sun, energy, and climate change*. Springer, 2023.

[7] A. Zahedi, “Maximizing solar PV energy penetration using energy storage technology,” *Renewable and sustainable energy reviews*, vol. 15, no. 1, pp. 866–870, 2011.

[8] S. A. Kalogirou, “Environmental benefits of domestic solar energy systems,” *Energy Convers Manag*, vol. 45, no. 18–19, pp. 3075–3092, 2004.

[9] S. Weckend, A. Wade, and G. A. Heath, “End of life management: solar photovoltaic panels,” National Renewable Energy Laboratory (NREL), Golden, CO (United States), 2016.

[10] K. A. Khan and M. A. Salek, “Solar photovoltaic (SPV) conversion: a brief study,” *IJARIIE*, vol. 5, no. 5, pp. 187–204, 2019.

[11] A. J. Nozik and J. Miller, “Introduction to solar photon conversion,” 2010, *ACS Publications*.

[12] Y. Abou Jieb and E. Hossain, *Photovoltaic Systems*. Springer, 2022.

[13] N. Zhang, D. Sutanto, and K. M. Muttaqi, “A review of topologies of three-port DC–DC converters for the integration of renewable energy and energy storage system,” *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 388–401, 2016.

[14] J. Cho, S. Jeong, and Y. Kim, “Commercial and research battery technologies for electrical energy storage applications,” *Prog Energy Combust Sci*, vol. 48, pp. 84–101, 2015.

[15] K. Xu, “Electrolytes and interphases in Li-ion batteries and beyond,” *Chem Rev*, vol. 114, no. 23, pp. 11503–11618, 2014.

[16] K. Garbesi, “Catalog of DC appliances and power systems,” 2012.

[17] F. A. Viawan and D. Karlsson, “Combined local and remote voltage and reactive power control in the presence of induction machine distributed generation,” *IEEE Transactions on Power Systems*, vol. 22, no. 4, pp. 2003–2012, 2007.

[18] K. M. Yavor, V. Bach, and M. Finkbeiner, “Resource assessment of renewable energy systems—A review,” *Sustainability*, vol. 13, no. 11, p. 6107, 2021.

[19] A. S. R. Subramanian, T. Gundersen, and T. A. Adams, “Modeling and simulation of energy systems: A review,” *Processes*, vol. 6, no. 12, p. 238, 2018.

[20] M. J. B. Kabeyi and O. A. Olanrewaju, “The levelized cost of energy and modifications for use in electricity generation planning,” *Energy Reports*, vol. 9, pp. 495–534, 2023.

[21] E. E. Akhigbe, N. S. Egbuhuzor, A. J. Ajayi, and O. O. Agbede, “Designing risk assessment models for large-scale renewable energy investment and financing projects,” *International Journal of Multidisciplinary Research and Growth Evaluation*, vol. 5, no. 1, pp. 1293–1308, 2024.

[22] B. O. Bilal, V. Sambou, P. A. Ndiaye, C. M. F. Kébé, and M. Ndongo, “Multi-objective design of PV-wind-batteries hybrid systems by minimizing the annualized cost system and the loss of power supply probability (LPSP),” in *2013 IEEE International Conference on Industrial Technology (ICIT)*, IEEE, 2013, pp. 861–868.

[23] E. Cuce, P. M. Cuce, and T. Bali, “An experimental analysis of illumination intensity and temperature dependency of photovoltaic cell parameters,” *Appl Energy*, vol. 111, pp. 374–382, 2013.

[24] S. Narendiran, S. K. Sahoo, and R. Das, “Control and analysis of MPPT techniques for maximizing power extraction and eliminating oscillations in PV system,” *International Energy Journal*, vol. 16, no. 3, 2016.

[25] D. Abbes, A. Martinez, and G. Champenois, “Life cycle cost, embodied energy and loss of power supply probability for the optimal design of hybrid power systems,” *Math Comput Simul*, vol. 98