People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
UNIVERSITY ABOU-BEKR BELKAID - TLEMCEN

MASTER'S THESIS

Submitted to:

FACULTY OF SCIENCES – DEPARTMENT OF PHYSICS

For the award of the degree of:

MASTER'S DEGREE IN PHYSICS

Specialization: Energy Physics and Renewable Energies

By:

M^lle^ HAIBAOUI AICHA ELBATTOUL

On the theme

Design of a Hybrid Service Station (Photovoltaic – Wind) with an Automated Energy Management and Fuel Level Monitoring System

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Publicly defended on June 21 2026 in Tlemcen before the jury composed of:

Mr KARAOUZENE Lotfi Ibrahim	MCA	University of Tlemcen	President
Mr BABA AHMED Nassim	MCA	University of Tlemcen	Supervisor
Mme BERREZOUG Hiba Imane	MCA	University of Tlemcen	Examiner

Année Universitaire : 2025 ~ 2026

Dedication

I dedicate this work to my beloved parents, whose unconditional love, sacrifices, and support have always guided me throughout my life and studies.

*To my dear sisters, **Bassmala** and **Douaa**, and my beloved brother, **Youcef**, for their love, encouragement, and constant presence.*

To my roommates and classmates, for the unforgettable memories, friendship, and support we shared during this academic journey.

*A special dedication to my dear friend **Nedjwa (Joujou)**, for her kindness, encouragement, and unwavering support.*

To everyone who contributed, directly or indirectly, to the completion of this work.

With love and gratitude.

ACKNOWLEDGMENTS

First and foremost, I thank Almighty God, who guides us along the right path.

If someone had told me at the beginning of the writing process that the acknowledgments would be the hardest part to write, I wouldn't have believed them. And yet, I can now confirm it. They often represent the most read part of a thesis, or at least the one a reader will naturally look at first. It is therefore a matter of finding the right words for everyone, while ensuring no one is forgotten. I will thus begin by thanking anyone I might have inadvertently missed later on. Contrary to popular belief, a thesis is not the result of purely solitary work. Beyond being an incredible scientific experience, it is also an unforgettable human adventure that allowed me to meet and work alongside extraordinary people who contributed, directly or indirectly, to the completion of this work. It is therefore naturally and with the utmost sincerity that I will now thank everyone who surrounded me during these past few years!

I would like to express my deepest and warmest thanks to my supervisor, **Dr. BABA AHMED Nassim**, Associate Professor (*Maître de conferences « A »*) at the University of Tlemcen. I wish to extend my full gratitude to him for his technical, scientific, and moral support; for his encouragement, and above all, for the patience and availability he consistently showed toward me.

I would also like to extend my thanks to all the members of the jury for the time they dedicated to reviewing this manuscript.

In particular, I thank **Mr. KARAOUZENE Ibrahim LOTFI**, Associate Professor (*Maître de conferences « A »*) at the University of Tlemcen, for agreeing to chair this Master's jury. I am highly honored by the presence of **Mrs. SARI HASSOUNE (née BERREZOUG Hiba Imane)**, Associate Professor (*Maître de conferences « A »*) at the University of Tlemcen, and I thank her for agreeing to serve on this jury as an examiner. Finally, I thank all the members of the jury for their expertise and the valuable critical insight they brought to my work.

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Complete List of Abbreviations Used in the Memoire

AC — Alternating Current

AI — Artificial Intelligence

CDER — Centre for the Development of Renewable Energy

CO■ — Carbon Dioxide

DC — Direct Current

EMS — Energy Management System

EV — Electric Vehicle

FF — Fill Factor

GHI — Global Horizontal Irradiation

GHG — Greenhouse Gas

HAWT — Horizontal Axis Wind Turbine

HOMER — Hybrid Optimization Model for Multiple Energy Resources

HV — High Voltage

IEC — International Electrotechnical Commission

IRR — Internal Rate of Return

kW — Kilowatt

kWh — Kilowatt-hour

kWp — Kilowatt-peak

LFP — Lithium Iron Phosphate

LV — Low Voltage

MPPT — Maximum Power Point Tracking

MPP — Maximum Power Point

NASA — National Aeronautics and Space Administration

NPC — Net Present Cost

PR — Performance Ratio

PSH — Peak Sun Hours

PV — Photovoltaic

PVs — Photovoltaic Systems

PVsyst — Photovoltaic System Software

PWM — Pulse Width Modulation

RF — Renewable Fraction

SCADA — Supervisory Control and Data Acquisition

SOC — State of Charge

STC — Standard Test Conditions

UTC — Coordinated Universal Time

VAWT — Vertical Axis Wind Turbine

WT — Wind Turbine

General introduction

General Introduction:

The steady increase in energy consumption carried on by population grouth, industriel development, and quick technical advancement is now causing a significant changes in the global energy industry. The need for sustainable and clean energy solutions has increased due to this growing demand, the depletion of traditional fossil fuels, and increasing of environmental concerns about greenhouse gas emissions. In this context, the renewable energy sources have become a key solution, offering a pathway toward a long-term economic stability, environmental protection, and energy sustainability.

Renewable energy technologies especially solar photovoltaic (PV) and wind energy systems, have attracted a lot of interest, due to their maturity, flexibility, and decreasing installation cost. These resources are particularly important for decentralized applications where fuel dependence is high or grid reliability may be restricted, such distant facilities and service stations. A viable way to increase energy dependability, lower operating costs, and lessen environmental effect is through the integration of hybrid renewable energy systems, which combine multiple sources with energy storage and backup generation

The design, modelling, and optimization of a hybrid photovoltaic–wind energy system with battery storage at a gasoline service station located in Aboutachfine, Tlemcen, Algeria, are the main objectives of this project. The goal is to determine the best way to cut diesel usage while increasing the contribution of renewable energy by evaluating the technical, economic, and environmental performance of various energy configurations.

The work is organized into three major chapters in order to achieve this objective. First of all, the first chapter gives an extensive overview of renewable energy sources, with a concentration on solar photovoltaic and wind energy, including their concepts, components, benefits, and possibilities for integration into hybrid systems. Then, the second chapter lays the theoretical and methodological foundation for the study, by presenting the mathematical models of each system component, including PV panels, wind turbines, battery storage, inverters, and energy management techniques. Additionally, it describes the system design and input parameters utilized for modelling and analysis, as well as the simulation tools employed in this work, namely PVsyst and HOMER Pro.

Ending with the third chapter, which shows and discusses the simulation results obtained from the suggested system settings. In terms of energy output, fuel savings, renewable fraction, system dependability, and economic indicators like energy cost and investment return, it contrasts the performance of standalone and hybrid systems.

Using this methodical approach, the study hopes to show that hybrid renewable energy systems are a good substitute for traditional diesel-based production, especially when it comes to lowering operating costs and increasing energy autonomy.

Chapter I:

Background and Literature Review on Renewable Energy Systems

I.1. Introduction:

The world's energy consumption is currently increasing steadily as a result of industrial and technical advancements as well as population growth. This has raised environmental issues related to the usage of fossil fuels and resulted in the depletion of conventional energy sources. In this context, renewable energy have emerged as a sustainable solution that helps satisfy energy demands while reducing adverse environmental effects and ensuring sustainable development.

In general, this chapter aims to provide a comprehensive overview of renewable energies by examining their idea, historical evolution, and various key sources, including hydropower, biomass, geothermal, solar, and wind energy. The chapter focusses on solar photovoltaic and wind energy, describing the types, components, and practical uses, also their working principles. Additionally, hybrid system that integrate several renewable energy sources are examined, also stand-alone systems.

Finally, the chapter discusses wind energy, its components, advantages, and disadvantages, highlighting the integration and complementarity between solar and wind energy to improve energy production and ensure a continuous supply.

I.2. Renewable energy:

Renewable or sustainable energy is extracted from natural sources, such as water, sunlight and wind, which are continuously replenished, this sourced characterized by their abundance, which is due to their ability to renew themselves faster than they are consumed , also by their distribution in our environment. On the other hand we have non-renewable energy like fossil fuels are finite such as: coal, oil and gas, which are very dangerous to the environment because of their destructive emissions of greenhouse gasses like carbon dioxide. Knowing that this non-renewable sources take millions of years to form. Emission from renewable energy production are much less than burning fossil fuels which is the major source of greenhouse gasses emissions, this highlights the need to adopt renewable energy sources as a primary source of energy production in the world, given its potential to combat climate change and reduce risks.

In addition, renewable energy contribute to creating more than three times as many jobs as fossil fuels, it has led to becoming more: economical and cost-effective in more countries, as a result, this enhances their economic, environmental and social value. [1]

I.3. Historical Overview:

A. Solar energy:

- In 1839, the French Antoine Edmond Becquerel was the first to point out this particular conversion of energy.
- In 1930, the development of cells with cuprous oxide and then with selenium.
- In 1958, the first generators were used for satellites Vanguard in Florida. [1]

B. Wind energy:

- In 1988, the American scientist Charles F. Brush built the first wind turbine capable of producing electrical power with 12kw.
- In 1920, the French scientist named George J.M. Darrieus develops the concept of a rotor with a vertical axis. [1]

C. Biomass:

- In 1840, the first commercial use of biomass gasifier, the device is made in France.
- In 1900, the German inventor Rudolf Diesel demonstrates that a diesel engine can run on peanut oil, so vegetable oil is used as a replacement for diesel. [1]

D. Geothermal energy:

- In 1904, in the city Lardello in Italy, the geothermal energy was used for the first time to produce electricity.
- In 1911, the opening of the first power plant. [1]

E. Hydraulic energy:

- In 1883, the Italian engineer designed and installed the first electric generator in Sondrio powered by hydraulic force.
- In 2015, China occupies a clear first place globally in the world. [1]

I.4. Different sources of renewable energy:

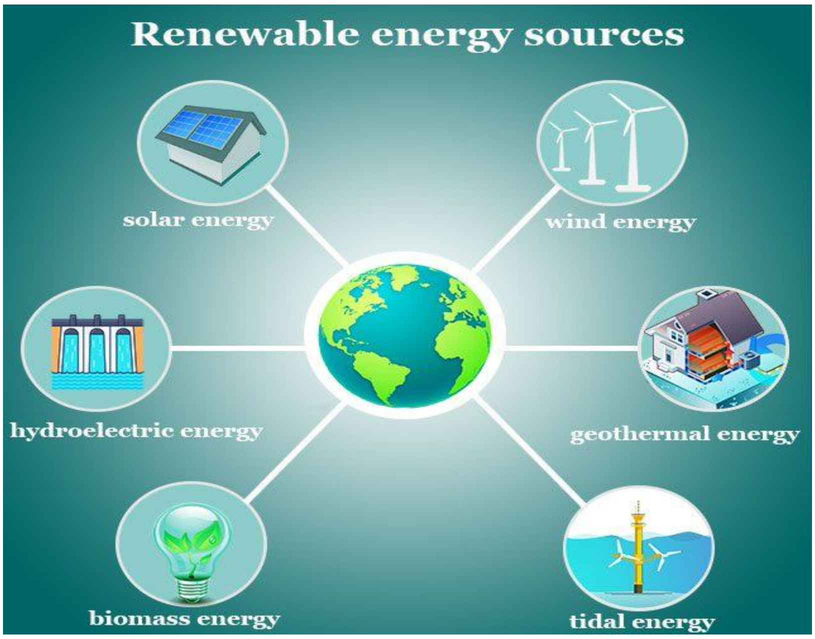


Figure I.1: Different renewable energy sources

I.4.1. Hydraulic energy:

Hydraulic from "**HYDRAULICOS",** a Greek word composed of:" **HYDRO** "meaning water, and "**AULOS** "meaning pipe.

This energy is obtained from the movement of water, such as water flowing in dams, rivers or waterfalls. This energy can be converted from mechanical energy into electrical energy so that it can be used in our daily lives. This conversion is done by using turbines and generators. [1]

Different forms of energy are used in hydraulic:

- Kinetic energy (by velocity), like in hydroelectric turbine.

- Potential energy (from gravity), like a water tower.
- Pressure energy used in industrial and mobile hydraulic systems.

Several techniques are used in this energy sector such as dams, tidal and turbines. [1]

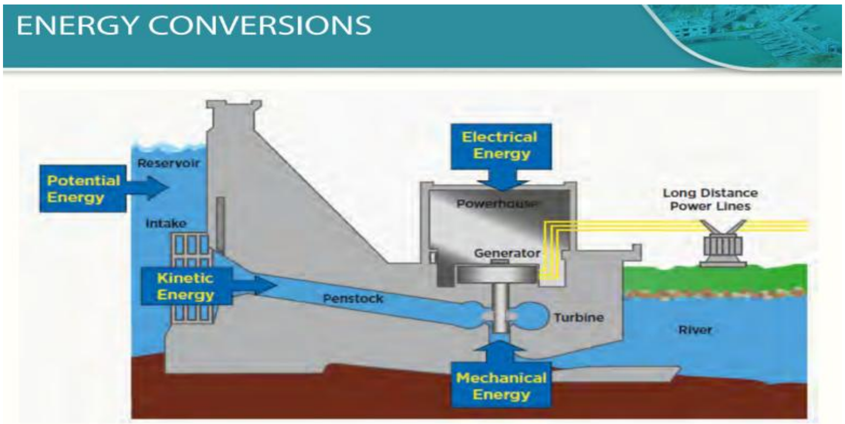


Figure I.2: Hydro Energy

I.4.2. Geothermal energy:

Geothermal comes from the Geek words "GEO" means" earth" and" THERMOS" "heat ", present both the science that studies the internal thermal phenomena of the earth also the technology used to exploit it .

This energy is obtained by circulating a fluid deep underground, it heats up as it comes into contact with the hot rocks and flows back to the surface with thermal energy. This heat can be converted into electricity or used directly for heating. [1]

- **Operating principal of geothermal energy:**

Water stored underground is converted by the Earth'heat into steam, which then spins a turbine and generates electricity with a generator. [2]

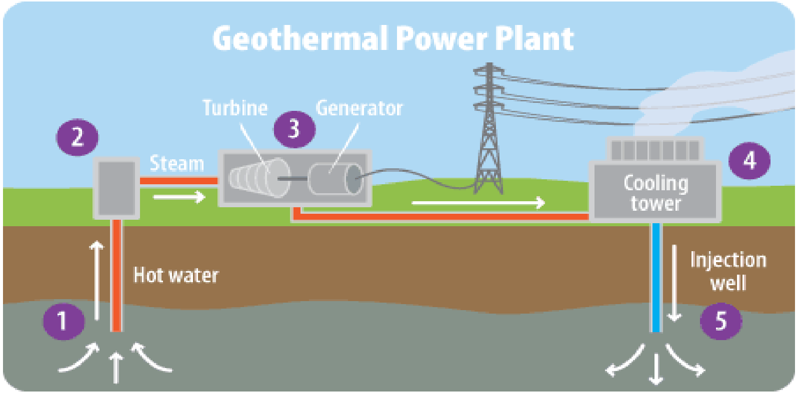


Figure I.3: Geothermal energy

1. Using a well and excessive pressure, the water extracted from the deep subterranean sources
2. The water changes into steam because the pressure decreases, when it arrives at the surface.
3. A generator that generates electricity is linked to a turbine powered by a steam.
4. Once the steam leaves the turbine, it is chilled and condensed in a cooling tower, returning to water.
5. The cycle is then recommenced by pumping the cooled water down underground.[2]

I.4.3. Biomass energy:

Biomass represents all types of living organisms present in a particular environment or ecosystem in a renewable or recurring manner. Its sources include wood, animal waste, municipal waste, food crops and agricultural residue such as" corn stover ". Through photosynthesis Plants produce sugars, proteins, fats and carbohydrates as a result of converting sunlight into energy, storing some of this energy within their seeds, roots and tissues. Wood represents the largest source of energy among the various biomass resources.

Biomass is a vital source of fuel in many countries, especially for cooking and space heating, particularly in developing countries. Additionally, its applications are expanding in the production of transportation and electricity generation in many developed nations, helping to lower carbon dioxide emissions from fossil fuel use. [3]

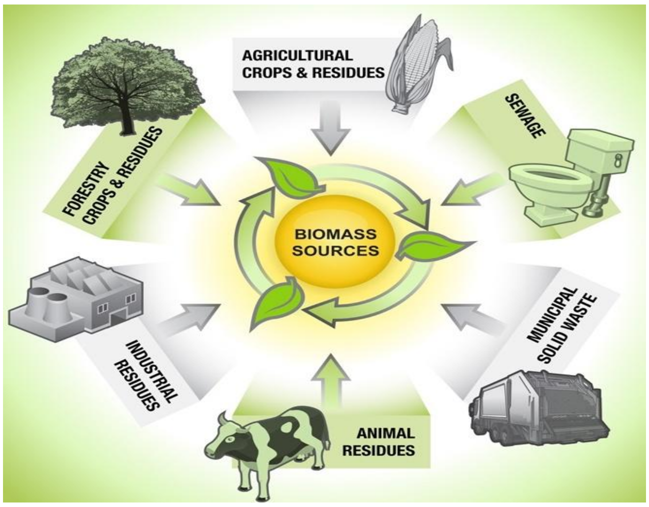


Figure I.4: Biomass resources

I.4.4. Solar energy:

Solar energy is produced by thermonuclear reactions occurring in the sun, where hydrogen atoms are constantly transformed into helium. Heat and electromagnetic radiation are released large quantities during the process. The sun's electromagnetic radiation propagates in all directions across space. Although only a small fraction of this radiation reaches the Earth, it is still considered an important source of energy because the power received by the Earth is thousands of times greater than the total energy consumed by humans. One of the purest and most plentiful renewable energy sources on the planet is solar energy. Around 1.4 kW/m² of energy is delivered by the radiation flux known as "the solar constant".In comparison, the energy that reaches the exposed surface of the Earth is approximately 10,000 times greater than the total power consumed by humans, which is about 18 TW from all sources such as oil, nuclear, coal and others. Therefore, the impending energy crisis would be solved if we could capture even a small fraction of that. Advanced technologies allow both businesses and individuals to use solar power in their daily lives in various ways, such as solar water heaters and home heating systems, which help reduce energy expenses and environmental impact. This energy is inexhaustible and sustainable. [4]

There is two types of solar energy:

- Solar thermal energy
- Photovoltaic solar energy [4]

- **Definition of solar thermal energy:**

Solar thermal energy refers to technologies that convert sunlight into heat rather than electricity using solar collectors that absorb solar radiation. This heat can be used directly or transferred by a circulating fluid, such as air or water, for applications like domestic heating and hot water production.

Because of solar energy can be extracted in two different forms: solar thermal energy and photovoltaic energy, there are two similar types of solar technologies: solar collectors which are used to produce heat, and photovoltaic panels, which are used to generate electricity. [4]

• Solar panels: how do they operate and why choose them?

A heat transfer fluid that circulates in pipes implanted below a glass surface is heated by sunlight absorbed by a solar thermal panel. Than the heat is transferred to a storage tank and used to warm water for household usage.

How a solar thermal panel operates:

- Solar heat absorption: Using a glass surface, the panel collects solar radiation and converts it to the pipes holding the thermal-transfer fluid.
- Heated fluid circulation: The warm liquid travels to the storage tank via the electrical system after being heated by the sun.
- Heat transfer: A heat transfer distributes the heat to the household water source.
- Hot water utilization: Bathrooms, showers and heating are typical household uses for the hot water.[5]

• Different types of solar thermal panels:

Depending on their intended use, solar thermal panels come in various types, because of their economic value and optimum performance, flat plate collectors are the most popular and suitable for domestic application. While unglazed collectors are mainly used for pool water heating as a more affordable but less productive option, high-efficiency tube collectors enable superior efficiency especially under cold or low-sun climatic conditions.

Up to 70% of home's hot water requirements can be supplied by a well-constructed system, which helps conserve energy.

However, considering its benefits, solar thermal energy still accounts for 0.2% of France's annual heat consumption. [5]

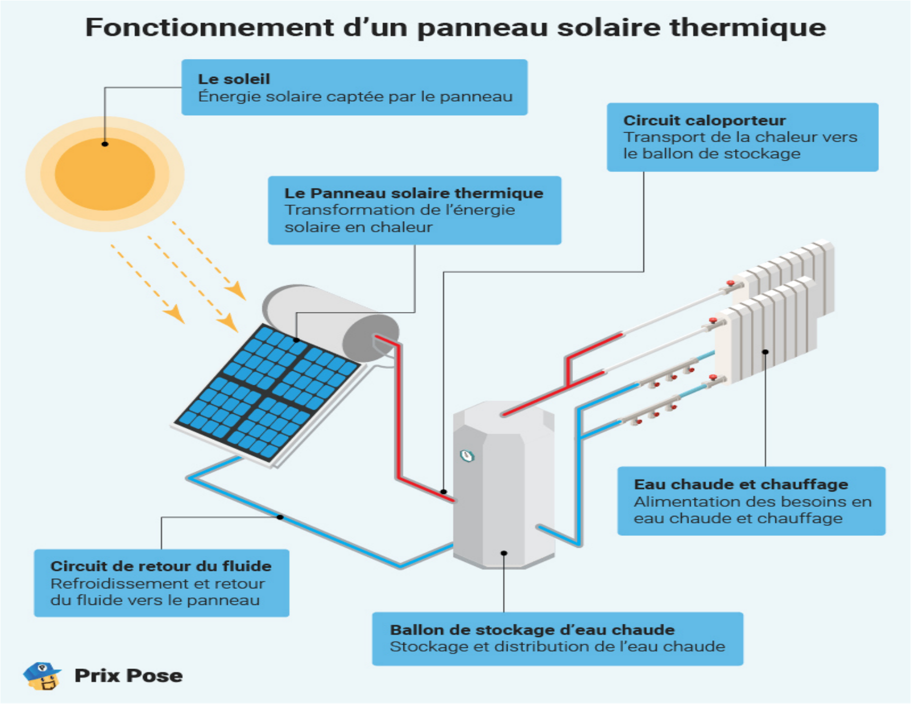


Figure I.5: The operation of a solar thermal panel

- ## Advantages of solar thermal panels:

- Long lifespan: as a result of right care and maintenance, a solar thermal panel can last 20 to 30 years.
- Attractive return on investment: due to energy savings, the return can frequently be achieved in 5 to 10 years.
- Raised certificate of home energy efficiency.
- Eco-friendly and renewable: supports the energy revolution with lower CO2 emissions
- Energy savings: an extensive decrease in hot water and household heating costs.[5]

Disadvantages of solar thermal panels:

- High installation cost: ranging from 4000£ to 7000£, some households may be encouraged because they find it expensive.
- Sunshine dependency: depending on climatic conditions: if it is winter or cloudy days so there will be less efficiency, sometimes requiring additional heating (e.g., electric heaters or stoves).
- Space needed: to maximize heat production, a well-exposed roof area is crucial.
- Maintenance requirements: good performance depends on regular cleaning of the collectors and periodic checks of the heat transfer fluid.[5]

Definition of photovoltaic solar energy:

Photovoltaic energy (PV) is one of the most renewable energy technologies used today, it refers to the process of the direct convert sunlight into electricity without producing pollution or greenhouse gas emissions, using semiconductors materials. Solar cells are responsible of converting incoming light from the sun into electrical energy, the cost of this solar cells was high, making solar modules the dominant element of a PV system. To reduce system cost, focus the incoming sunlight using either mirrors or lenses. [6]

The term"photovoltaic" is derived from the Greek word "Photo", mean light and "Volta" refers to the Italian scientist Alessandro Volta, a pioneer in the study of electricity. Although Volta did not discover photovoltaic energy, he played a fundamental role in the history of science by discovering a continuous electric current to develop future electrical systems and modern renewable energy technologies including:

- Batteries used to store photovoltaic energy.
- Electrical circuits and energy storage technologies.

In 1939, Alexandre Edmond Becquerel was first observe the photovoltaic effect, when he found that light could generate an electric current in certain materials. [6].

• Working principle of photovoltaic systems (PVs):

The PV effect is the basis of how solar systems function, the fundamental parts are the solar cells, which are made of semiconductors materials like silicon. When sunlight hits the surface of this cells, photon transfer their energy to electrons in the material.

As a result, electrons become excited and start to move, creating an electric current, this current is primarily direct (DC), which depending on the application, can be used directly or converted into alternating current (AC), via an inverter.

The quality of semiconductors material, the intensity of solar radiation and environmental factors such as temperature and shade all effect how effective this process is. [6]

• Components of a PVs:

A basic photovoltaic system consists of several essential components that coorperate to produce and manage electricity:

- **PV modules:**

  The fundamental elements that are responsible about transforming solar radiation into electrical energy are the photovoltaic cells. PV module is formed by combining many cells in series to generate the necessary voltage (48V, 12V….). The smallest unit that may be used in a solar energy system is this module. A several modules are assembled to create solar panels, which are subsequently connected to construct PV fields. There are two primary methods for linking the components of a PVS: parallel and series connections. The system can deal with various energy needs by using a parallel connection to boost power production and a series connection to enhance electrical voltage. This cells are mainly composed of crystalline silicone, either polycrystalline or monocrystalline, which may also be created as thin-film utilizing modern technologies. In addition, to ensure system efficiency and safety, protection devices such as anti-return diodes are installed to prevent reverse current and by-pass diodes are used to minimize overheating. [7]

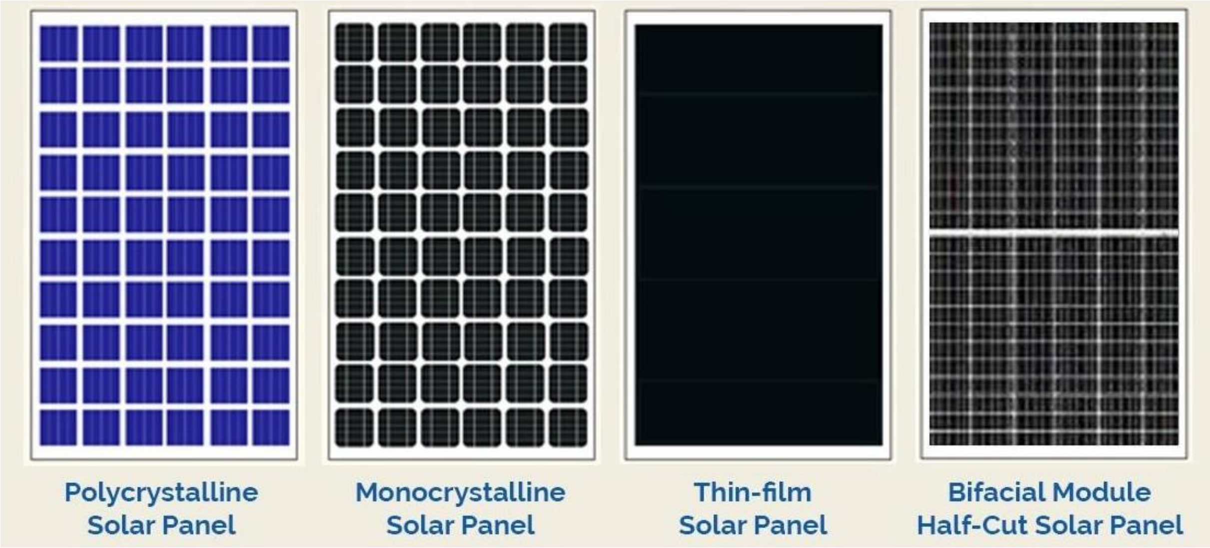


Figure I.6: Types of PV modules

- **Batteries**:

Battery technologies are used to accomplish the requirement of daily or seasonal storage, because solar energy is not always available in PVs. In low power installations, lead-acid batteries with flat plates are the most used batteries. There are other types as well, such nickel-cadmium batteries, but in the other hand they are most costly with voltage regulation issues. In the long term, energy storage technologies are anticipated to emerge and develop throughout time. Batteries can be configured in series to obtain the required voltage level, while parallel arrangements are used to enhance the overall capacity and satisfy the necessary energy requirements for system autonomy. The two electrodes that make up the battery are a positive electrode and a negative electrode that are immersed in an electrolyte, which is a solution of sulfuric acid at different concentrations. Both the voltage of the solar modules and the properties of the direct current (DC) loads influence the selection of battery voltage. Moreover, the total number of batteries is determined according to the desired period of energy autonomy. Batteries are connected to a charge controller in photovoltaic systems, which manages the charging process and guarantees a secure supply of electricity to the loads. [8]

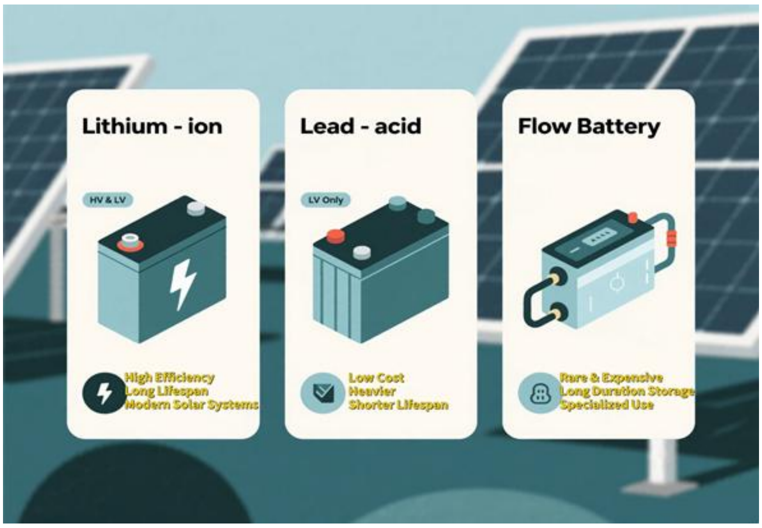


Figure I.7: The 3 types of batteries used in solar energy

- **Definition of High-voltage and Low-Voltage batteries:**

High-voltage batteries are devices which store energy that run at levels that are capable of reaching thousands of volts, and are usually higher than 100 volts. Back to their ideal performance and efficiency, they are primarily used in big residential, commercial, and large-demand solar power system. [9]

On the other hand, we have low-voltage batteries, typically at lower voltage level, constantly between 12 and 48 volts. In light of their basic design, affordability, and their accessibility of installation, they are the best choice to use in rural areas or small-scale solar systems. [9]

There are many factors such as cost, efficiency, current and voltage that highlight the distinctions between those two types of batteries, as illustrated in the table below:

Aspect	HV Batteries	LV Batteries
Voltage	Above 100V	From 12V to 48V
Current	Reduced	Superior
Efficiency	Superior	Reduced
Cost	High	Low
Installation	More complex	Easier
Applications	Large systems	off-grid systems, small systems
Heat generation	Less	More
Safety	Strong safety protocl	Safer because its reduced voltage
Lifespan	Long (espesially lithium-ion)	Long but depends on usage
Maintenance	Complex, need professional maintenance	Simple, routine monitoring is sufficient

Table I.1: The differences between HV and LV [9]

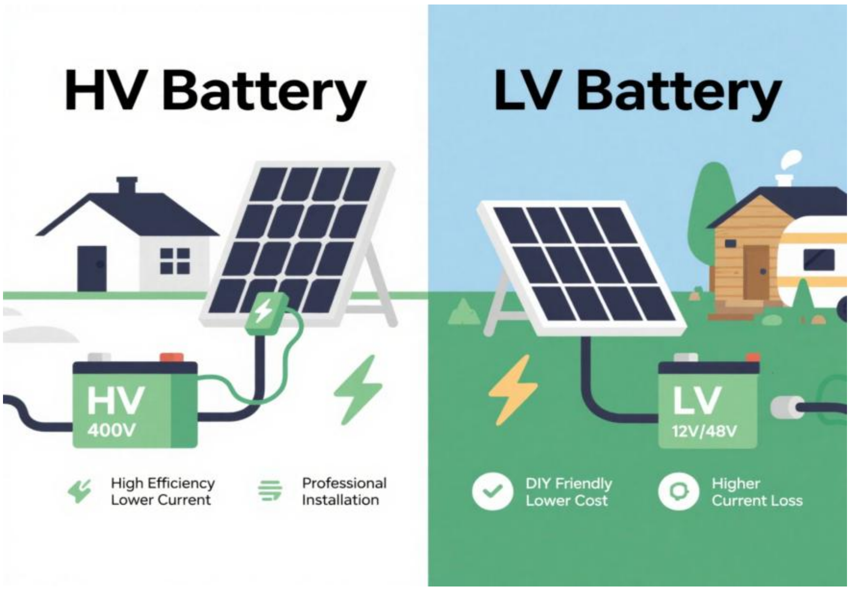
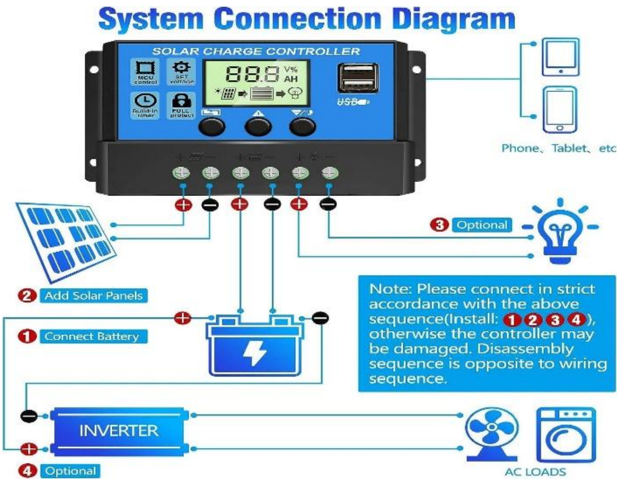


Figure I.8: HV and LV batteries

- **Charge controller (regulator):**

This device controls the voltage and current flowing from the panels, and manages the charging and discharging of batteries in a solar system and block reverse current at night. When the battery reaches a high level of charge, it protects it by disconnecting the photovoltaic modules in order to avoid battery overheating. In contrast, in the case of excessive discharge the controller uses an automatic cut-off device in order to stop the power supply to the loads and protect the batteries from deep discharge. So we can say that without this mechanism, the batteries may experience water loss. Furthermore, the controller has the ability to compensate for temperature changes, which allows the system to adapt how it operates. Usually, it is installed between the batteries and the photovoltaic array. [10]

Figure I.9: Solar charge collector



Note: Please connect in strict accordance with the above sequence(Install: ①②③④), otherwise the controller may be damaged. Disassembly sequence is opposite to wiring sequence.

Figure I.10: System connection diagram

- **Types of Charge Controller:**
- MPPT (Maximum Power Point Tracking _ more efficient):

Is an advanced devise that optimizes energy through intelligent tracking, by transforming the excess voltage into additional current, using DC-DC converter, enabling the system to collect as much energy as possible from the PV array, which varies depending on solar irradiation and temperature conditions. So we obtain as results: raising energy-efficient (10–30 %), In addition, it is ideal for medium-sized and large-scale PV systems. [10]

- PWM (Pulse Width Modulation):

It offers direct connection with controlled switching, by working as a switching mechanism between the PV modules and the battery, this device does not actually control the voltage of the photovoltaic panel; rather, it forces the panel to operate at a voltage close to the battery voltage. In order to regulate charging, it attaches the solar panel directly to the battery, and progressively reduces the current. This type mostly used in small solar systems, due to its simplicity and low cost. [10]

- **Inverter (DC /AC Converter):**

Most of electrical appliances use alternating current (AC), so this device converts direct current DC produced by solar modules or stored in batteries, into standard alternating current AC electricity. Therefore, it is necessary to integrate an inverter into the PV system while powering AC loads. This conversion enables the functioning of household appliances, and guarantees compatibility with traditional electrical systems, also inverter plays an important role in system protection, by incorporating features like overload defense and short-circuit prevention. Inverters can operate different mode depending on the setup of the system: in grid-connected system, generated electricity is synchronized with the utility grid, while in stand-alone systems, power is sent directly to the loads. In hybrid systems, the inverter manages multiple energy sources in order to guarantee peak performance and power uninterrupted supply. The produced signal may be either a square wave or a pure sinusoidal wave. [11]

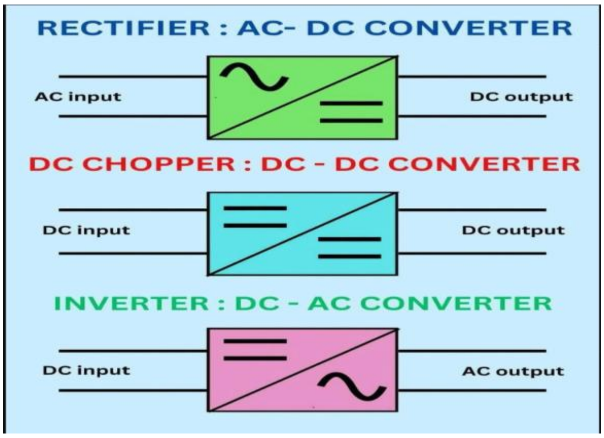


Figure I.11: Inverter types

- **Cables and wiring:**

Cables ensure energy transmission between units, by linking different parts of photovoltaic system, they may be working in enclosed systems, exposed or embedded conduits, and permanent configurations both indoors and outdoors without protection. They are also used for power delivery in regular buildings and similar civil engineering infrastructures. [11]

Figure I.12: 1/1 KV PV-Solar Photovoltaic cable

- **Protection devices:**

They include: bypass and blocking diodes, fuses and circuit breakers, their main function is to prevent damage to the system, by protecting components, which is necessary for both system longevity and safety. This devices protect against errors, overcurrent, and reverse current. [11]

- **Mounting structure:**

The PV modules are supported by the mounting framework, which also preserves their correct orientation with regard to the sun. It need to deal with external factors like rust, oxidation and wind, so could guarantee stability and optimum panel installation. [11]

- **Electrical load:**

Generally, anything that uses power is an electric load, and the usage is measured in watts. Is any part of a circuit that uses electrical energy and transforms it into another forms, usually light or heat, for example: lamps, laptops, motors, electric vehicles (EVs). The properties of the system components are defined by their electrical specifications and usage voltages. Therefore, careful selection of loads is required, with high-efficiency devices preferred wherever possible. The loads's technical characteristics must be documented in order to precisely determine the necessary power output of the system, once the loads to be provided by the mini PV system are identified. [10]

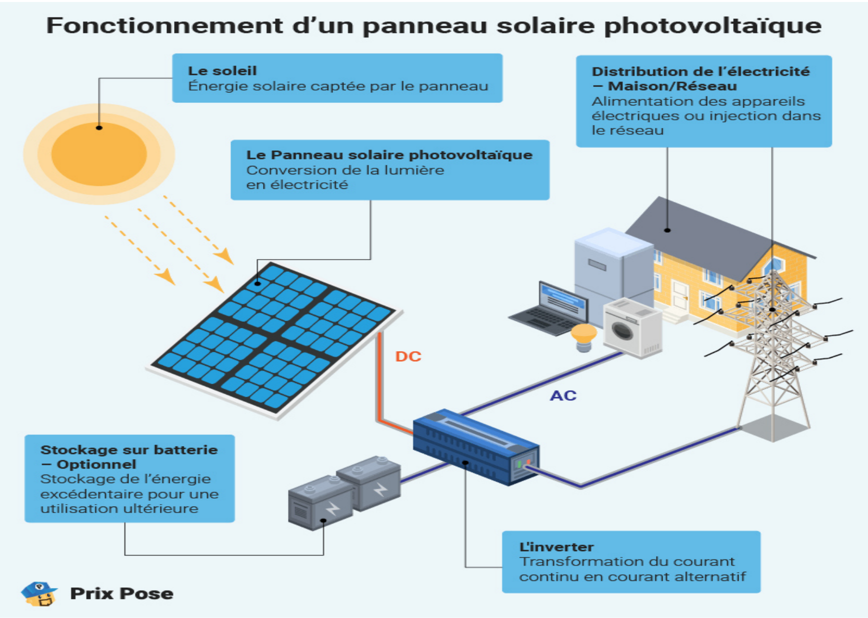


Figure I.13: The operation of photovoltaic solar panel

- **Comparison table:**

Solar thermal and photovoltaic technologies can be used to broadly categorize solar energy systems. Photovoltaic systems are primarily used to generate electricity for a wide range of uses, while solar thermal systems are generally used to create heat for applications including space and water heating. These two technologies differ in cost, efficiency, terms of energy output and applications. In order to better understand their characteristics and determine the best option depending on the purpose and climatic conditions, it is necessary to compare photovoltaic and solar thermal systems. This table shows that solar thermal systems are more efficient and economical at producing heat, making them suitable for domestic heating applications. On the other hand, photovoltaic systems provide greater flexibility, because they offer power that maybe utilized for a variety of reasons. As a result, the choice between this two technologies is based on the particular energy needs, financial constraints and application specifications. [12]

Criteria	Solar Thermal Systems	Photovoltaic Systems
Energy Output	Heat energy	Electrical energy
Main Applications	Water heating, space heating, pools	Electricity supply, appliances, grid systems
Efficiency	High (for heat production)	Moderate (for electricity conversion)
Installation Cost	Relatively low	Higher
Energy Storage	Thermal storage (water tanks)	Electrical storage (batteries)
Dependence on Sunlight	High	High
Flexibility	Limited to heating uses	Highly versatile

Table I.2: Comparison between photovoltaic and solar thermal systems

Based on the particular energy needs, financial constraints, and application specifications [12], [13].

I.5. Types of Photovoltaic Systems (PVs):

Depending on PVs configuration, application and connection to the grid, they can be classified into different types:

I.5.1. Stand-Alone PV Systems (Off-Grid Systems):

An autonomous energy that operates without any connection to the public electricity grid, is known as a stand-alone solar system. It is made especially to provide electricity to isolated areas where grid access is not available or economically impractical. [14]

Batteries are unite of charge used in this system to store energy to use it later when solar radiation is not enough or during nighttime. While charge controller is a device in role of regulate the current and voltage coming from solar panels to protect the batteries from either overcharging or deep discharge. So this system is designed to offer energy demand of a specific load improving system stability and durability. [14]

- **System components:**

- PV modules
- Batteries
- Charge controller
- Inverter (in case AC loads are used) [14]

- **Systems Applications:**

- Telecommunications stations
- Control systems and remote monitoring
- Water pumping system for agriculture
- Isolate and rural houses [14]

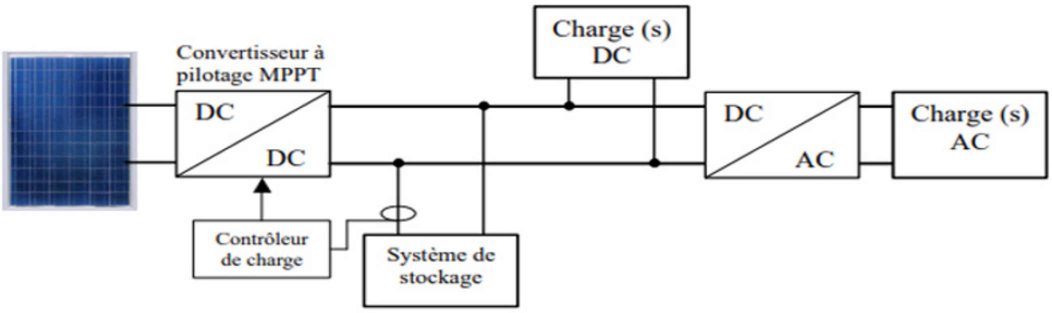


Figure I.14: Stand-alone photovoltaic installation

I.5.2. Grid-Connected PV Systems (On-Grid Systems):

This system is called "Connected" because its connection to the public utility grid, also it runs in synchrony with it, so they are used in urban areas where the electrical grid is available. In addition to providing the electricity to the demand, this system has the ability to transfer extra energy to the grid in order to compensate the shortcomings of lack solar energy production. Usually these systems don’t need batteries to store energy produce. [15]

• Systems Applications:

- Systems for delivering electricity in cities
- Commercial and offices buildings
- Residential buildings (solar panels on the roof)
- Huge solar power plants
- Industrial premises [15]

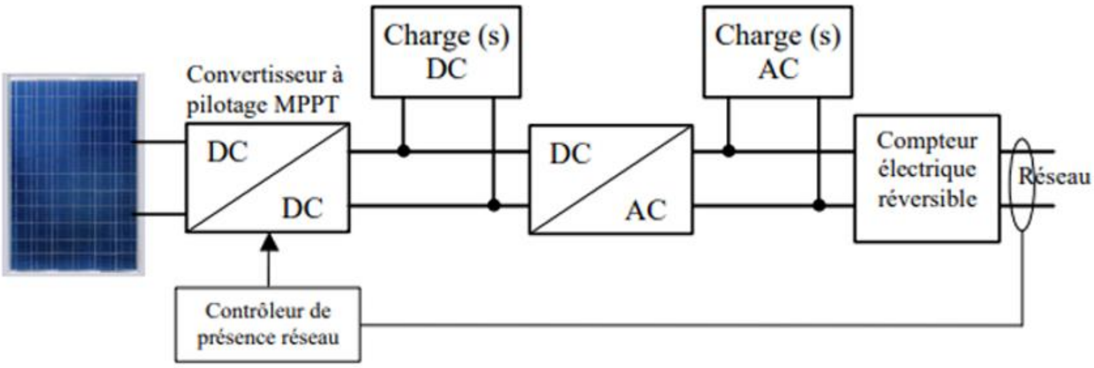


Figure I.15: Grid-connected photovoltaic installation

I.5.3. Hybrid systems:

An energy system that includes solar electricity generation with one or more other energy sources, like batteries, diesel engines or electrical grid, is recognized as a hybrid photovoltaic system. The main goal of this configuration is to guarantee a continuous and dependable energy supply throughout different operation conditions. Photovoltaic panels generate electricity during periods of intense solar irradiation, to supply the equipment and charge the batteries. The system uses stored electricity in the batteries, when solar energy is not enough such as at night or during cloudy weather. [16]

- **System components:**

In general, hybrid system consists of:

- Photovoltaic panel
- Charge controller
- Battery storage
- Inverter DC into AC
- Extra source for additional support (a power generator or grid) [16]

- **Different combinations of hybrid systems:**
- **Hybrid photovoltaic-wind-diesel system:**

Using hybrid systems, photovoltaic and/or wind power have connection to other energy sources. This usually consists of diesel, propane and gasoline-powered backup generators and wind turbines. This technology is destined for buildings that are not grid-connected, both residential or commercial, and batteries are equipped in most of hybrid systems. [16]

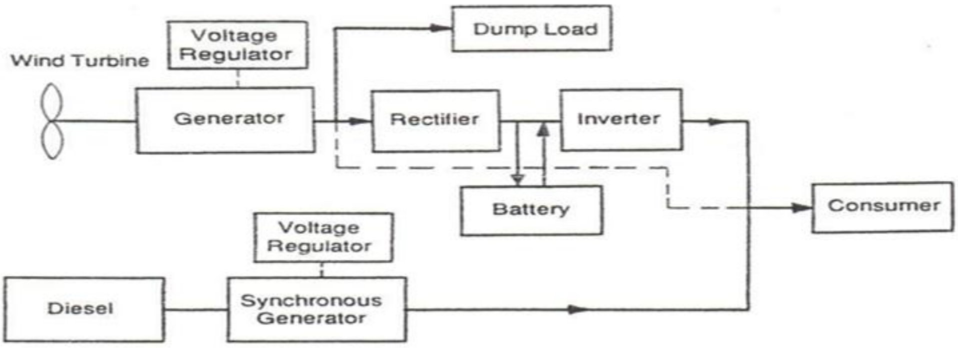


Figure I.16: Hybrid photovoltaic-wind-diesel system

- **Hybrid photovoltaic-battery and fuel cell system:**

Fuel cell technology takes the role of the diesel generator in this arrangement.

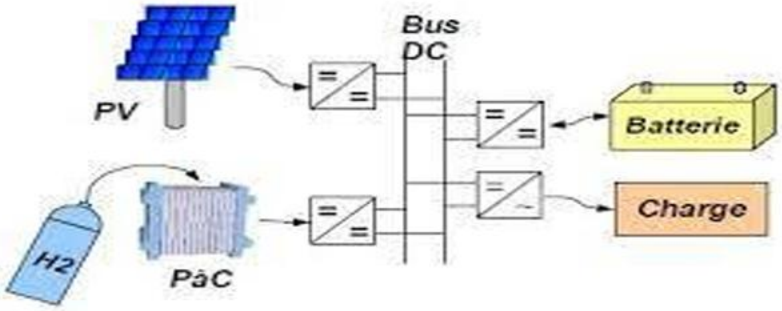


Figure I.17: Hybrid photovoltaic-battery and fuel cell system

- **Hybrid photovoltaic-wind system:**

This system combines a battery, and two supporting energy sources, solar and wind. The economic model of each system has a major impact on how electrochemical is applied to optimize solar and wind energy. [17]

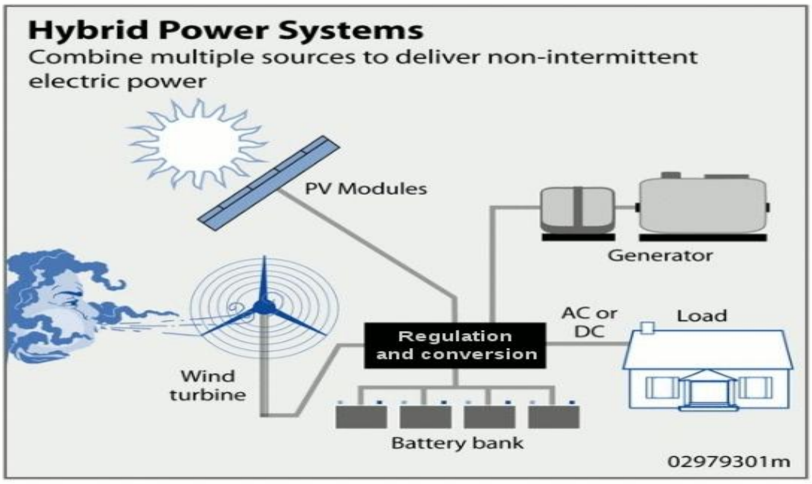


Figure I.18: Schematics of a hybrid system

Advantages and disadvantages of a hybrid system:

Advantages:

- Improved dependability and supply continuity due to the combination of various sources of energy (wind + solar or generator).
- Decreased dependence on a particular source (e.g., if solar power drops, wind or generators take over).
- Hybridization increases system performance by optimizing energy efficiency.
- Decreased battery size and cost, because there are various sources of energy.
- Ideal for essential applications (remote system, service stations and telecom stations). [17]

Disadvantages:

- Increased initial cost comparing with Diesel generator, due to multiple components.
- The complexity of system design and control, needs energy management system (EMS).
- Maintaining numerous technologies and devices is more complicated.[17]

I.6. Wind energy:

Wind energy is a form of renewable energy that uses wind turbine to converts the kinetic energy of moving air masses into consumable electrical power. This energy comes from the irregular heating of the Earth's surface that results from solar radiation, which causing air movement and pressure variations. Wind energy is considered sustainable, clean and largely accessible in many parts of the world. [18]

I.6.1. Principle of operation:

Aerodynamic principles determine how a wind turbine operates. As a result of wind flowing over the turbines blades, a pressure variations are created between the blades'top and lower surfaces, producing lift and causing the rotor to rotate. This rotating motion is transmitted by a shaft, often via a gearbox, sent to a generator, which turns mechanical energy into electrical energy. [19]

A small part of the wind's kinetic energy is removed as it flows through the rotor, which causes the wind speed downstream of the turbine to decrease. [19]

I.6.2. Wind characteristics:

The main factors that determine how much energy is available in the wind are: wind speed, air density and the swept area of the turbine blades. Since the energy created is proportional to the cube of wind velocity V^3, so we can say that wind speed has the greatest influence among all of these factors. This connection indicates that a major rise in electricity generated may result from just a minor increase in wind speed. Consequently, careful location choice is an important step in wind energy installations to optimize their performance and efficiency. [20] [21]

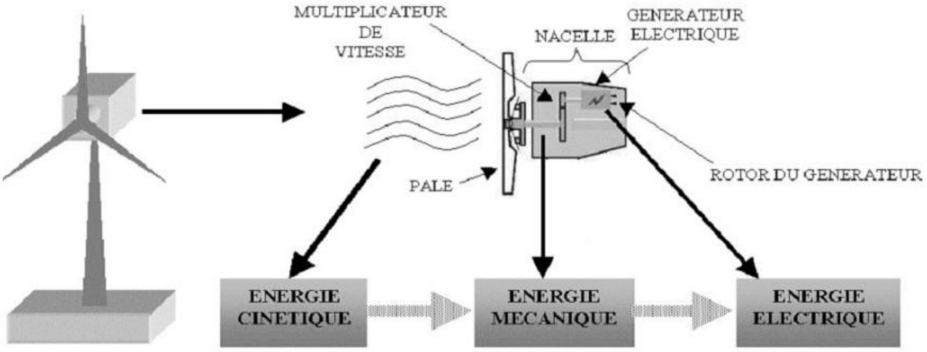


Figure I.19: Transform the kinetic energy into electrical energy

I.6.3. Types of wind turbines:

Depending on the orientation of their rotational axis, wind turbines are typically classified into two main types:

- **Horizontal axis wind turbines (HAWT):**

The aforementioned turbines are the most often used due their high efficiency and capacity to produce large quantities of electricity. They include long blades that rotate like a giant fan facing the wind, around the horizontal axis. They are usually installed in huge wind farms-tall towers. [22]

Figure I.20: Horizontal axis wind turbines (HAWT)

- **Vertical axis wind turbines (VAWT):**

This type of turbines rotate around a vertical axis and can operate whatever the direction of wind.

However, they are mainly used in urban areas or small-scale settings and are less efficient.

Although being around for centuries, vertical axis wind turbines are less popular than the horizontal versions. The primary raison of this is that they do not benefit from the higher wind speeds available at higher elevations, unlike horizontal-axis wind turbines. [22]

Figure I.21: Vertical axis wind turbines (VAWT)

- ## Comparison Between HAWT/VAWT:

The primary advantages and disadvantages of both horizontal and vertical axis wind turbine are presented in the following table: [22] [19]

Type of Turbine	Advantages	Disadvantages
Horizontal Axis Wind Turbine (HAWT)	Excellent efficiency Availability to high winds Advanced control system	Expenssive Need an orientation Maintenence is difficult at height
Vertical Axis Wind Turbine (VAWT)	Inexpensive Operates in all wind directions Easier maintenence (near to the ground)	Less effeciency Vabrations caused by mechanics Limited control options

Table I.3: Comparison of horizontal axis and vertical wind turbine axis

From this table, we conclude that HAWTs are typically used for large-scale power production due to their great level of efficiency, however VAWTs are preferable for urban and small-scale projects. [19]

According to their maximum power, wind turbines may also be divided into three groups, as the following table illustrates: [19]

Scale	Blade diameter	Power rating
Small scale	**<12 m**	**<40 kW**
Medium scale	**Between 12 and 45 m**	**From 40 kW to 1 MW**
Large- scale	**>46 m**	**>1 MW**

Table I.4: Wind turbine categories according to their power

I.6.4. Different parts of wind turbine

A wind turbine is made of several essential components that cooperate to convert wind energy into electrical energy. These components are designed to guarantee secure operation in a variety of wind conditions and efficient energy conversion. [20]

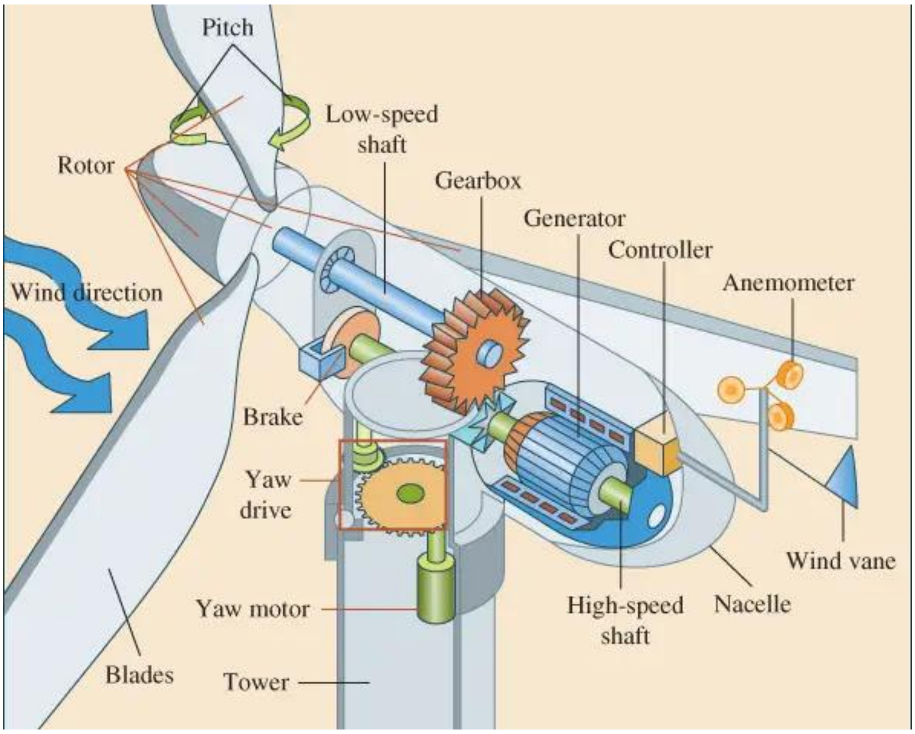


Figure I.22: Components of a wind turbine

- **Rotor (Hub and blades):**

It made up of central hub-connected aerodynamic blades. It represents the primary part in charge of catching wind energy. The rotor rotates as a consequence of lift forces generated when wind flows over the blades. Wind speed, length and blade design are factors that affect energy collection efficiency. [20]

- **Blades:**

The aerodynamic profile of the blades is particularly designed to resemble the wings of an airplane. Their principal role is to convert wind energy from kinetic energy into mechanical rotational energy. The turbine's performance and efficiency can be affected by the quantity and shape of its blades. [20]

- **Hub:**

The hub transfers the rotating motion produced by the blades to the mechanical transmission system by connecting them to the main shaft. [20]

- **Gearbox:**

The rotor's rotating speed is increases using a gearbox to a higher speed that is ideal for the generator. However, there are several modern wind turbines use direct-drive systems to operate without need a gearbox. [21]

- **Generator:**

This device converts the mechanical energy into an electrical energy. It is a key factor that controls the wind turbine's electrical output. [21]

- **Nacelle:**

On the top of the tower, directly behind the rotor blades, there is a protective housing called the nacelle. It serves as the brain and engine room of the wind turbine, housing and protecting the essential mechanical and electrical parts such as gearbox, shafts, and generator, from harsh weather conditions. [20]

- **Tower:**

The tower raises the wind turbine to a level where wind speeds are higher and more stable especially while supporting the entire construction. Higher towers often produce energy. [20]

- **Main shaft and drive train:**

The rotor's rotational motion is transferred to the gearbox through the main shaft. It is in the position of successfully transferring mechanical energy to the generator and is a part of the drive train system, which also includes the shaft, gearbox, and generator. [20]

- **The control system:**

It guarantees optimal performance by modifying turbine operation based on wind speed and guards against system breakdown under harsh conditions. So in general, control system observes and manages the turbine wind's functioning. [20]

- **Yaw system:**

In order to optimize energy capture, we use the yaw mechanism which allows the turbine to rotate and coordinate with the direction of the wind. [19]

- **Brake system:**

In order to maintain safety, the braking mechanism is used to stop the turbine during repair or in case of extremely high wind speeds. [19]

Sensors:

Present important variables including wind direction, temperature, and wind speed are measured using sensors. The control system uses this measurements in order maximize turbine performance. [20]

I.6.5. The wind:

The massive movement of air in the Earth's atmosphere caused by pressure gradients brought on by unequal surface heating from the sun is known as wind. [21]

These pressure variations create airflow to migrate from high-pressure areas to low-pressure areas, producing typical wind patterns with different directions and speeds. Additionally, heat is absorbed differently by both water and land, causing in temperature fluctuations that lead to pressure variations. Moreover, wind direction is affected by how the Earth rotates (Coriolis effect), and as a result of that, complicated atmospheric circulation patterns. [19]

I.6.6. Advantages of wind energy:

Wind energy offers a variety of major benefits, including:

- It is a sustainable and renewable energy.
- It decreases dependence on fossil fuels.
- Free greenhouse gas emissions during operation.
- It is preferred in rural and remote areas.
- After installation, its functioning and maintenance costs are minimal.
- It can be included into hybrid energy system (PV-Wind). [23] [20]

I.6.7. Disadvantages of wind energy:

Wind energy has multiple drawbacks despites its advantages, which are:

- It is periodic and depends on the presence of wind.
- Both noise and visual effect could result from it.
- It demands specific areas where the wind speed is sufficient for it performance.
- It needs large areas for installation.
- High cost of installation.
- In hybrid system, advanced control system are necessary to ensure system efficiency. [24] [25]

I.6.8. Complementarity between wind and solar energy:

Since both solar and wind energy originate from solar radiation, so they are inseparable linked. The unequal heating of the Earth's surface causes by solar irradiation produced variations in both temperature and pressure values, which create wind. As consequence, wind energy may be regarded as an indirect shape of solar energy. Additionally, wind and solar resources function in a complimentary way: solar energy is more accessible periods of high irradiation, in the other hand, wind energy is frequently stronger under low sun circumstances. This complementarity makes hybrid wind-solar systems extremely effective, which increases energy dependability and ensure an extra continuous power flow. [19] [21]

I.7. Conclusion:

This chapter introduces various renewable energy sources and their growing role in addressing the energy and environmental challenges facing the world. It reviews the fundamental characteristics of hydropower, geothermal, biomass, solar, and wind energy, with a focus on photovoltaic and solar thermal systems, which are among the most widespread and commonly used technologies today.

The chapter also discusses the components of photovoltaic systems, their different types, and their various applications. Furthermore, it examines hybrid systems that allow for the simultaneous utilization of multiple renewable energy sources, thus enhancing reliability and energy efficiency. Finally, it highlights the importance of integrating solar and wind energy as a promising solution for ensuring stable and sustainable energy production. The knowledge presented in this chapter provides a necessary theoretical foundation for understanding and studying the energy system employed in this work and the results that will be presented in subsequent chapters.

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Chapter II :

Design Metodology and Sizing of the Hybride PV-Wind Energy System

II.1. Introduction

Before any component of a hybrid energy system can be selected or any simulation result can be trusted, it is necessary to establish a clear and methodical theoretical foundation that describes the physical behavior of each subsystem and the mathematical relationships that govern its operation. This chapter fulfills that requirement for the hybrid photovoltaic-wind energy station designed for the Aboutachfine service station in Tlemcen, Algeria.[1]

The chapter follows a logical and progressive structure. It opens with a description of the overall system architecture and the general sizing approach adopted in this study. It then presents the theoretical models and governing equations of the photovoltaic generator, the wind turbine, the battery storage system, the inverter, and the energy management strategy. Following this theoretical foundation, the two simulation software tools used to validate and optimize the design — PVsyst V8.1.2 and HOMER Pro — are formally introduced and described. The chapter then concludes with the presentation of the specific PV array configuration and simulation parameters used in this study, which are drawn directly from the PVsyst simulation environment. A summary table of all design parameters closes the chapter before the conclusion. [1]

This order is intentional: equations and physical models are presented first because they belong to engineering science and are independent of any software. The software tools are introduced afterward because they are the instruments used to apply and validate those models. The specific simulation configuration is presented last because it results from the use of those tools and should only be discussed once the reader understands both the theory and the software. No simulation results or output graphs are included here; those are reserved entirely for Chapter III. [1]

II.2. Site Selection and Resource Assessment

II.2.1. Geographical Location of the Site:

The studied site is a service station located in Aboutachfine, Tlemcen. The climat in this areas is ideal for producing renewable energy, especially solar energy because of its high solar irradiation through the year. Moreover, the station has a high electricity consumption cause by fuel pumps, lights, refrigeration, and air condition systems. As a result, this area is ideal for the implementation and study of a hybrid photovoltaic-wind energy system. [2]

According to the Meteonorm 9.0 meteorological database used for the simulation, the geographical coordinates and site specificities service station in Tlemcen are summarized in the table below:

Parameter	Description /value
Project Site	Abou Tachfine, Tlemcen (Service Station)
Country	Algeria
Latitude	34.90° N
Longtitude	1.30° W
Altitude	820m
Time Zone	UTC +1
Data Source	Meteonorm 9.0

Table II.1: Geographical coordinates and site location data [2]

II.2.2. Analysis Of The Available Solar And Wind Energy Potential:

Algeria's national area is home to numerous advantages locations decentralized energy generation. The availability of meteorological data was an important consideration in the site selection process because this study focuses on hybrid photovoltaic-wind power system.

A. Solar Energy Potential in Algeria:

Algeria has one of the world's greatest solar energy potential because of its geographical position and the size of the Sahara Desert. The nation is well-suited for photovoltaic and solar thermal applications due to its extremely high solar irradiation level and long sunshine duration through the year.[3]

According to the Center for the Development of Renewable Energy (CDER), the majority of nation has more than 2000 hours of sunlight annually, with the Sahara and High Plateau areas can reach nearly 3900 hours. On a horizontal surface, the average daily global solar irradiation differs from 5.1 $kWh/m^2/day$ in the northern regions to about 6.6 $kWh/m^2/day$ in the southern desert areas. [3]

The development of large-scale solar power planets and hybrid renewable energy systems is significantly facilitated by these favorable climatic conditions. It stated that the Algerian Sahara's high radiation levels, open sky, and wide accessible land and places made her particularly useful. [3]

Furthermore, the sizing, modelling, and optimization of photovoltaic and hybrid PV-wind systems depend strongly on meteorological data provided by the CDER and the Algerian solar atlas. [3]

B. Solar irradiation at the Tlemcen site:

For our study case Tlemcen, the average solar irradiation is calculated to be around 5 kWh/m²/day, indicating that photovoltaic energy may be integrated into the hybrid renewable energy system explored in this paper. [3]

This map was provided by the Centre for Development of Renewable Energy (CDER) and illustrates the annual average global solar irradiation received on a horizontal surface in Algeria during the period 1992-2002.

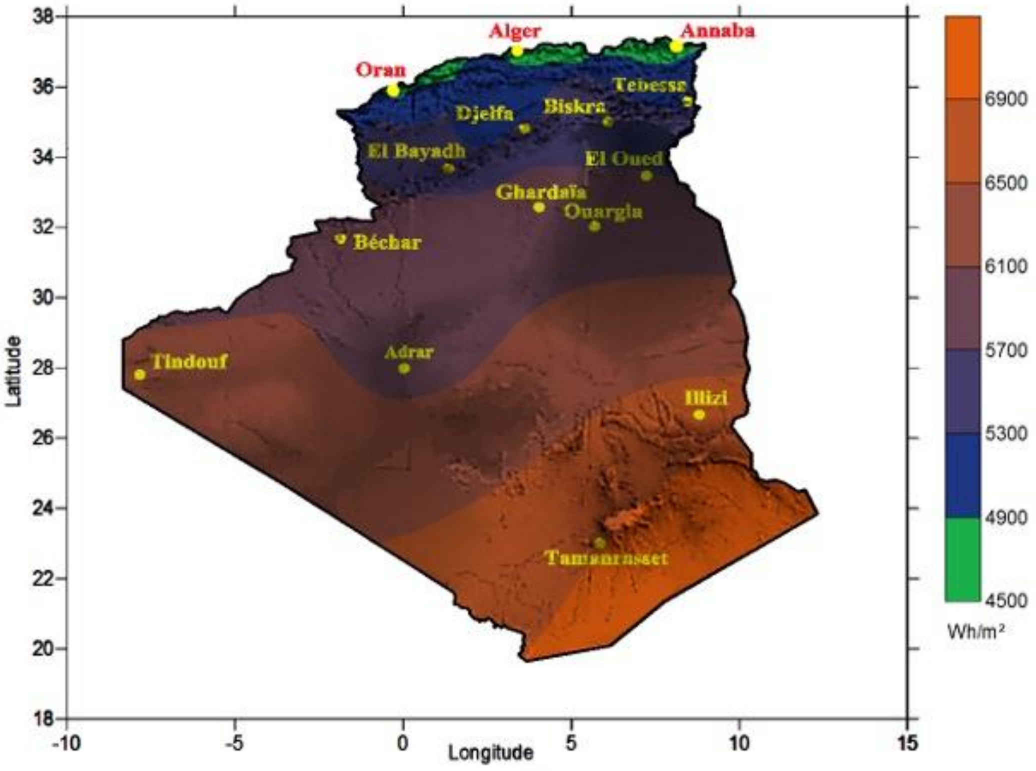

Figure II.1: Annual Average Global Solar Irradiation Received on a Horizontal Surface in Algeria (1992–2002).

C. Wind Energy Potential at the Tlemcen Site:

A crucial satge in the design of hybrid renewable energy systems is the evaluation of wind energy potential. In case of wind resources are available and suitable, this assessment makes it possible to assess for producing power in the area under study.

According to a scientific study carried out in the Tlemcen region, meteorological data and Weibull statistical distribution methods were used to examine the wind characteristics, the results showed that the average annual wind speed in the region of Tlemcen is about 2.42 m/s at a height of 10 m above ground level, and the average, while the average annual wind power density is about 49 W/m². These numbers show that the potential for wind energy in the area is humble to moderate. Nonetheless, Tlemcen's higher southern regions provide better wind conditions for wind energy exploitation.[3]

The study also showed that wind speed fluctuates throughout the year, with higher values should be being observed in the spring, especially in April. Furthermore, it is often windier during the day than at night. These fluctuations are important for estimating the energy production of wind turbines and maximizing hybrid system performance. [3]

Even if the area have a moderate wind energy potential, adding wind energy to the recommended photovoltaic-wind hybrid system is still beneficial as it enhances solar energy production and reduces reliance on the electrical grid. As a result, during the sizing and simulating of the hybrid renewable energy system suggested for the Aboutachfine service-station, the regional wind characteristics of Tlemcen were considered. [3]

II.2.3. Meteorological Data Analysis:

A comprehensive meteorological site evaluation was carried out in order to access in the renewable energy potential of the chosen area in Tlemcen. For the year 2024, high-precision satellite data was obtained from the NASA POWER database. Important design factors such daily worldwide horizontal solar irradiation, ambient air temperature, wind speed at a height of 10 meters, and relative humidity are all covered in this environmental baseline.[2] In addition, to confirming the site's abundant solar and wind resources, analyzing these combined characteristics is necessary for comprehending secondary atmospheric elements like humidity, which influence the hybrid system's long-term structural durability and thermal cooling procedures. The table below presents the entire monthly meteorological breakdown extracted from the satellite database. [2]

Month	**Solar Irradiation (kWh/m²/day)**	**Ambient Temp. (°C)**	**Wind Speed (m/s)**	**Relative Humidity (%)**
January	3.17	13.11	4.35	**63.4**
February	3.79	13.10	5.79	**63.6**
March	4.88	15.64	5.56	**54.9**
April	6.37	16.88	4.19	**52.2**
May	7.31	20.54	4.04	**46.8**
June	7.54	24.14	3.98	**42.3**
July	7.74	29.68	3.49	**37.1**
August	6.67	29.61	3.59	**39.4**
September	5.51	24.18	3.54	**49.8**
October	4.20	20.18	4.49	**56.5**
November	3.38	17.20	4.49	**59.3**
December	3.01	11.49	3.58	**61.1**
ANNUAL	**5.30**	**19.67**	**4.25**	**52.2**

Table II.2: Satellite-Derived Meteorological and Environmental Baseline Data for Tlemcen (Source: NASA POWER, 2024). [2]

A substantial yearly solar resource of 5.30 kWh/m²/day is can be seen by the analysis of NASA (2024) data for the Aboutachfine region, with highest summer irradiation approaching 7.74 kWh/m²/day in July. As we can see that the region benefits from a moderate relative humidity of 52.2%, an average temperature of 19.67 °C, and an average yearly wind speed of 4.25 m/s. From these parameters, we conclude that this region is stable and steady climate that is ideal for maximizing the efficiency and guaranteeing the durability of the hybrid system's components. [2]

II.3. Hybrid System Architecture and General Design Approach

II.3.1. Overall System Configuration

This study's hybrid energy is a standalone AC-coupled system with grid backup capabilities. The station's electrical are provided directly via a common AC bus in this architecture, which is connected to all energy sources and storage components using specific power converters. In general, the system comprises five primary subsystems, which are: the wind turbine generator, the photovoltaic array, the backup generator, the battery energy storage bank, and the hybrid power conditioning and energy management unit.[4]

Solar radiation is converted by the photovoltaic array into DC power, and that power then travels to AC bus via an MPPT controller and DC-AC converter. The bus is powered by the wind turbine's alternating current (AC) electricity through its own converter. Later we have a bidirectional inverter-charger links the battery bank to the system, storing extra energy during periods of high output and delivering it output is low. When both the renewable energy sources and the battery are insufficient to meet the present demand, the backup generator operates, which is the only time. This design provides the maximum level of operational flexibility by enabling independent management of each source and allowing the system to function in a range of generation-demand scenarios. [4]

II.3.2. Sizing Philosophy and Methodology

This study's size strategy is based on two-stage methodology. Starting with the first step, which explains the theoretical connections that regulate how each system components work, such as the battery storage system, wind turbine, and solar generator. We employ a number of equations to explain the system's physical behavior and establish the critical design parameters. Input data utilized to guide the design approach and determine the initial system configuration include the climatic conditions at the Tlemcen site, the station's electrical load requirement, and, of course, the desired renewable energy proportion. [5]

Moving on the second phase, professional simulation tools are employed to test the fundamental setups. The photovoltaic subsystem is modeled using PVsys V8.1.2, while HOMER Pro is used to simulate the entire hybrid system. These software tools allows for the study of energy output, system performance, and dependability by conducting through hourly simulations over a one-year period. Following that, the simulation results provide the last point of reference for design optimization and system validation.[5]

This methodology, which is applied throughout this chapter, guarantees that the system design is in line with both theoretical modelling principles and practical simulation results.

II.3.3. Definition of Dimensioning

Dimensioning is a crucial phase in developing a hybrid renewable energy system. It refers to the process of determining the proper size and capacity of the various system components, such as wind turbines, solar panels, batteries, and converters, in order to provide a consistent and reliable supply of electrical energy to meet demand. The primary goal of this procedure is to assure enough energy output while lowering the system's total cost. [17]

In general, in hybrid installations, the designer must properly combine renewable energy sources in order to achieve the best combination of technical performance and cost effectiveness. However, the dimensioning procedure is often problematic due to the high reliance of renewable energy sources on climatic conditions such as sun irradiation, wind speed, and temperature changes. As a result, the system's size must consider both the customer's energy consumption characteristics and the installation site's climatic factors. [18]

The ideal configuration that can provide the sufficient energy demand while reducing energy losses and operating expenses must be determined by the designer. For example, a larger photovoltaic array can minimize depend on battery storage, while having a smaller generating capacity might end up with excessive battery discharge and shorter battery lifetime. Therefore, to improve the hybrid system's dependability and efficiency, an optimal balance between production and storage capacity is necessary. [19]

II.3.4. Parameters to be Determined during the System Design

To guarantee the proper functioning and efficiency of the hybrid renewable energy system, several important parameters must be determined throughout the design process based on the system description and the study of its working principle. The main factors are summarized as follows:

- ✓ **Photovoltaic panel power:** The electrical power generated by the photovoltaic panel under standard test conditions, corresponding to a solar irradiation of 1000 W/m², is expressed in watt-peak (Wp) or (kWc). [17]
- ✓ **Battery capacity:** The quantity of electrical energy may be kept in the battery bank for later use is represented by this parameters. It is often expressed in Amper-hours, (kWh / Ah). [17] [22]

- ✓ **Nominal power of the wind turbine:** When the wind speed enables the generators to function at its nominal rotational speed, it corresponds to the electrical power generated by the wind turbine. It is often expressed by (KW). [20]
- ✓ **Load demand:** The primary input for system sizing is the service station's total electrical energy utilization (kWh/day or kWh/year). [17] [22]
- ✓ **Renewable energy fraction:** Which presents the percentage of total demand covered by whole the system including: PV and wind system, defining the level of energy independence of the hybrid system. It is expressed by (%). [19) [21]

II.3.5. Analytical Sizing Equations :

This parts describes the electrical behavior system's components such as PV and wind turbine generation, battery storage dynamics and their dependence on environmental conditions. Maximum photovoltaic power extraction is guaranteed by the MPPT controller, and the power conditioning is modelled utilizing inverter efficiency and balancing techniques. Finally, in order to guarantee system dependability and continuous supply, the energy management strategy also manages the total power flow between sources, storage, and load.

II.4. Photovoltaic System: Modeling and Sizing:

II.4.1. Operating Principle of the Photovoltaic Cell:

A solar cell is a device that turns sunlight into electricity. It works based on a connection called p-n junction inside this device. The cell has two parts: one part is called the n-type region, and the other part is called the p-type region. Here is how it works: when sunlight hits the device, it makes the electrons moves towards the n-type region. At the time, it makes the holes move, toward to the p-type region. This movement creates a kind of electricity called voltage, means that if we connect a wire to the device, the voltage can make electricity flow through the wire, this electricity can be used to powering things and loads.[6]

The way that sunlight is turned into energy with process is influenced by the type of material used and its quality, the intensity and spectral composition of the incident irradiance, the temperature of the cell when it is operating and the angle at which the sunlight strikes the surface. [6]

II.4.2. Basic Power Equation of a PV Cell:

The power equation, which it describes the instantaneous electrical power P generated at any active point on the current-voltage (I-V),[7] is the simplest basic electrical relationship of a photovoltaic cell or module:

$$P = V \times I \qquad \text{(II.1)}$$

- P — Electrical power produced by the cell or module (W)
- V — Terminal voltage across the cell (V)
- I — Current flowing through the external circuit (A)

The Maximum Power Point MPP, the primary operational goal of any photovoltaic system, is when this product reaches its greatest value. Predicting and optimizing this amount under real operating conditions, is the ultimate purpose of each other equation in this section.[7]

- ## Fundamental Equation:

Main function:

Explain how the solar cell behaves electrically when exposed to radiation.

The net current equation, which balances the light –generated current and the recombination/diffusion current, describes the electrical behavior of a solar cell[8]:

$$I = I_L - I_0 \left(e^{\frac{qV}{(nkT)}} - 1 \right) \qquad \text{(II.2)}$$

Where the elements represent:

- I: Net current flowing out of the cell.
- I_L(Light-generated current): The current generated by photon absorption. This is directly proportional to the incident solar irradiation.
- I_0(Dark saturation current): A measure of the recombination in the device; it represents the "leakage" or loss current.
- V: The voltage across the cell.
- q: The charge of an electron.
- T: The absolute temperature (in Kelvin).
- n: The diode ideality factor (usually between 1 and 2).

- k: The Boltzmann constant.

This formula describes the ideal scenario, which ignores ohmic and leakage losses. In the section named: The One-Diode Equivalent Circuit Model provides a more comprehensive formulation that accounting for series and shunt resistances.[8]

II.4.3. The One-Diode Equivalent Circuit Model

The photovoltaic cell is usually represented by a model in engineering tools. This model is called the one-diode circuit model. Sometimes The most widely adopted mathematical representation of a photovoltaic cell in engineering simulation tools is the one-diode equivalent circuit model, sometimes referred to as the single-exponential model or the five-parameter model. The photovoltaic cell model is good enough to show how the cell works with electricity. It is also so simple for computationally manageable. The photovoltaic cell has multiple parts: starting with photocurrent source. This source is connected in parallel with a diode. There is also a resistance, it accounts for junction leakage. There is a series resistance. This resistance represents losses, in the contacts and the semiconductor bulk of the photovoltaic cell. [8]

The photovoltaic cell model has a current-voltage relationship, which describes the current delivered by the photovoltaic cell. The net current is called I, It is delivered at a terminal voltage. The terminal voltage is called V. [8]

The current-voltage relationship of the photovoltaic cell model is expressed as:

$$\mathrm{I} = \mathrm{I_L} - \mathrm{I_0} \times \left(\exp\left(\frac{\mathrm{q} \times (\mathrm{V} + \mathrm{I} \times \mathrm{R_s})}{\mathrm{n} \times \mathrm{k} \times \mathrm{T}}\right) - 1\right) - \frac{\mathrm{V} + \mathrm{I} \times \mathrm{R_s}}{\mathrm{R_{sh}}} \tag{II.3}$$

Each one of this symbols has the following physical meaning:

- I — Net current delivered to the external circuit (A)
- I_l — Photogenerated current (A): the current produced directly by absorbed photons, linearly proportional to incident irradiance G
- I_0 — Diode dark saturation current (A): represents minority carrier recombination in the junction; strongly increases with temperature
- V — Terminal voltage across the cell (V)
- R_s — Series resistance (Ω): models contact resistance and resistivity of the semiconductor bulk
- $R_s^{=}$ — Shunt resistance (Ω): models leakage current paths across the p-n junction; a lower value indicates more recombination losses
- q — Elementary charge of the electron: 1.602×10^{-19} C

- n — Diode ideality factor (dimensionless, typically 1 to 2): accounts for non-ideal recombination mechanisms at the junction
- k — Boltzmann constant: 1.381×10^{-23} J/K
- T — Absolute cell temperature (K)

The quantity (n × k × T / q) is called the voltage V_t. It equals 25.85 mV at 300 K (27°C). We use this equation to generate the I-V characteristic curve. But it is implicit, in I so we solve it numerically or iteratively. This helps us get the curve at any given irradiance and temperature condition. The thermal voltage V_t is a part of this process. We need to calculate it to get the I-V curve. [8]

II.4.4. Photogenerated Current and Temperature Corrections

The temperature at which the cell operates and the incident irradiance both affect the photogenerated current I_l,[8] which is not constant. The following correction equation illustrates how it depends on these two factors:

$$I_L = \frac{G}{G_{ref}} \times \left[I_L^{ref} + \mu_{Isc} \times \left(T - T_{ref}\right)\right] \qquad \text{(II.4)}$$

- G — Actual incident irradiance on the cell surface (W/m²)
- G_{re}^{f} — Reference irradiance under STC: 1,000 W/m²
- I_{l}^{rrf} — Photogenerated current at STC conditions (A)
- $\mu^{I}{}_{s}{}^{c}$ — Temperature coefficient of short-circuit current (A/K); positive for silicon, typically 0.05 to 0.1%/°C
- T — Actual absolute cell temperature (K)
- T_{re}^{f} — Reference temperature under STC: 298.15 K (25°C)

I_0, the dark saturation current, is likewise sensitive to temperature. Since a rising I_0 immediately lowers the open-circuit voltage, its exponential temperature dependency is the main cause of PV cell efficiency declining at high operating temperatures, [8]:

$$I_0(T) = I_0^{ref} \times \left(\frac{T}{T_{ref}}\right)^3 \times exp\left[\frac{q \times E_g}{n \times k} \times \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \qquad \text{(II.5)}$$

- I_0^{rrf} — Dark saturation current at STC (A)
- E^G — Bandgap energy of the semiconductor; for silicon: $E^G \approx 1.12$ eV at 300 K

The temperature thing is really important at the Tlemcen site. This is because the cells can get very hot during summer sometimes hot as 60 to 70 degrees Celsius, when the sun is shining and the air is also hot. This heat makes the solar panels produce power than they should compared to what they are supposed to produce. The PVsyst simulation takes this into account with a thermal loss factor, which's, like a special number $U^c = 20$ W/m^{2}K that helps figure out how much power is lost because of the heat. [8]

II.4.5. Key Operating Points: I_s^c, V_o^c, and Maximum Power Point

Three reference operating points that completely describe a PV cell's electrical behavior under certain environmental conditions from its I-V characteristic curve.[6]

The current that flows when the terminal voltage is zero (V=0) is known as the short-circuit current or, or I_s^c. It roughly equals the photogenerated current under ideal conditions:

$$I_{sc} \approx I_L \qquad \text{(II.6)}$$

The voltage of a circuit when it is open is called the open-circuit voltage V_o^c. This is the voltage at the terminals when no external current is flowing through the circuit, which means (I = 0). To find the open-circuit voltage V_o^c we need to solve the equation for these conditions,[10] so it gives:

$$V_{oc} = \frac{n \times k \times T}{q} \times ln\left(\frac{I_L}{I_0} + 1\right) \qquad \text{(II.7)}$$

The maximum power point MPP is the point where the product of voltage and current's at its highest. Basically, this happens when the product P = V × I reaches its maximum value. The maximum power P_{mpp} and the corresponding Fill Factor FF are defined like this, [6]:

$$P_{mpp} = V_{mpp} \times I_{mpp} \qquad \text{(II.8)}$$

$$FF = \frac{P_{mpp}}{V_{oc} \times I_{sc}} = \frac{V_{mpp} \times I_{mpp}}{V_{oc} \times I_{sc}} \qquad \text{(II.9)}$$

- V_{mpp} — Voltage at the maximum power point (V)
- I_{mpp} — Current at the maximum power point (A)
- FF — Fill Factor (dimensionless); ranges from 0.70 to 0.85 for commercial crystalline silicon modules; higher values indicate better cell quality.

The Fill Factors measures how square the I-V curve is and represent the losses produced by the cell’s series and shunt resistances]. [6]

II.4.6. Performance Ratio and Specific Production :

Two standard indicators are used to evaluate the performance of a photovoltaic system in a way that is independent of its size and installation location. Starting with:

The Performance Ratio PR: the ratio of actual yearly energy delivered to the theoretical maximum assuming the array always functioned at Standard Test Conditions STC efficiency, [9]:

$$PR = \frac{E_{actual}}{P_{peak} \times H_{ref}} \qquad \text{(II.10)}$$

- $E_{a}{}^{c}{}_{tual}$ — Annual useful energy delivered to the load (kWh/year)
- $P_{pea}{}^{k}$ — Nominal PV peak power under STC (kWp)
- $H_{re}{}^{f}$ — Annual irradiation in the collector plane expressed in peak sun hours (kWh/m²/year)

The specific production Y^{f} is a location-independent performance statistic that calculates the annual energy output per unit of installed of peak power, [9]:

$$Y_f = \frac{E_{actual}}{P_{peak}} \qquad \text{(II.11)}$$

IEC 61724-1:2021, "Photovoltaic System Performance – Part 1: Monitoring," International Electrotechnical Commission, Geneva, Switzerland, 2021.

II.4.7. PV Array Pre-Sizing Equation :

The target solar energy percentage, the daily demand, and the available Peak Sun Hours at the site are used to analytically determine the required PV array peak power,[5]:

$$P_{PV} = \frac{f\ \ _{solar} \times E_{daily}}{PSH \times \eta_{sys}} \qquad \text{(II.12)}$$

- P_{pv} — Required PV array peak power (kWp)
- f_{solar} — Target fraction of daily load to be covered by solar (dimensionless)
- $E^{d}{}_{a}{}^{l}{}_{l}{}^{y}$ — Average daily energy demand (kWh/day)
- PSH — Peak Sun Hours: daily average GHI in kWh/m²/day; 5.30 h/day for Tlemcen (NASA POWER, 2024)
- $\eta_{s}{}^{y}{}_{s}$ — Overall system efficiency factor accounting for MPPT, wiring, temperature, mismatch, and inverter losses; typically 0.75 to 0.85

Applying this equation for the Aboutachfine station with $E^{d}{}_{a}{}^{l}{}_{l}{}^{y} \approx 580$ kWh/day, PSH = 5.30 h/day, $f_{solar} = 0.50$, and $\eta_{s}{}^{y}{}_{s} = 0.80$, [5]:

$$P_{PV} = \frac{0.50 \times 580}{5.30 \times 0.80} \approx 68.4\ kWp \qquad \text{(II.13)}$$

II.5. Wind Energy System: Theoretical Modeling and Equations:

II.5.1. Kinetic Power in Wind :

The kinetic energy of moving air masses is the source of wind energy. The instantaneous kinetic power available in undisturbed wind for a stream of air with density ρ passing through the rotor swept area A at the velocity V is, [6]:

$$P_{wind} = \frac{1}{2} \times \rho \times A \times v^3 \tag{II.14}$$

- ρ — Air density (kg/m^3); at sea level and 15°C: $\rho \approx 1.225$ kg/m^3; at 820 m altitude and 20°C: $\rho \approx 1.12$ kg/m^3
- A — Rotor swept area (m^2); $A = \pi \times R^2$ where R is the rotor radius
- v — Free-stream wind speed at hub height (m/s)

The fundamental feature of wind energy is the relationship between power and wind speed: doubling wind speed increases available power by eight. This is why even small improvements in hub height, which use the shear effect to access more powerful winds produce disproportionately large increases in annual energy output. [6]

II.5.2. The Betz Limit and Power Coefficient:

Since the downstream air must continue to flow, no wind turbine can fully collect the kinetic energy from the wind that passes through it. The Betz limit was established in 1919 when Albert Betz theoretically proved that the highest extractable proportion of wind kinetic energy is 16/27 ≈ 59.3%, [6] the rotor's mechanical power extraction is expressed as:

$$\boldsymbol{P_{mech} = C_p \times \frac{1}{2} \times \rho \times A \times v^3} \tag{II.15}$$

- C_p — Power coefficient (dimensionless); $C_p \leq 16/27 \approx 0.593$; commercial turbines typically achieve $C_p = 0.35$ to 0.50

Accounting for mechanical transmission efficiency η_{me}^{ch} and generator efficiency η^{G}_{en}, the net electrical output is, [6]:

$$P_{elec} = \eta_{mech} \times \eta_{gen} \times C_p \times \frac{1}{2} \times \rho \times A \times v^3 \tag{II.16}$$

II.5.3. Wind Speed Variation with Height: The Hellmann Power Law:

Wind speed increases with altitude above the ground due to decreasing surface friction effects. This vertical variation is modeled using the empirical Hellmann power law, [10]:

$$v(h) = v_{ref} \times \left(\frac{h}{h_{ref}}\right)^{\alpha} \qquad \text{(II.17)}$$

- v(h) — Wind speed at the target hub height h (m/s)
- v_{re}^{f} — Measured reference wind speed at height h_{re}^{f} (m/s); standard meteorological height: 10 m
- h — Hub height of the wind turbine (m)
- α — Hellmann surface roughness exponent; $\alpha \approx 0.143$ for flat open terrain

For the Tlemcen site, using $v_{re}^{f} = 4.25$ m/s at 10 m (NASA POWER, 2024), [2] and a hub height of 30 m with $\alpha = 0.143$:

$$v(30) = 4.25 \times \left(\frac{30}{10}\right)^{0.143} \approx 4.25 \times 1.161 \approx 4.93\, m/s \qquad \text{(II.18)}$$

II.5.4. Wind Turbine Power Curve

The actual electrical output of a wind turbine as a function of wind speed is defined by its manufacturer power curve, measured in accordance with IEC 61400-12. Three threshold wind speeds characterize the operating envelope, [11]:

- Cut-in speed v^{cI}: minimum speed at which the turbine begins generating, typically 2.5 to 4 m/s.
- Rated speed v_r: speed at which rated power is reached, typically 10 to 15 m/s.
- Cut-out speed $v^{c}{}_{o}$: maximum speed above which the turbine shuts down for protection, typically 20 to 25 m/s.

The piecewise mathematical model of the power curve is, [11]:

$$P(v) = 0 \qquad for\ v < v^{cI}\ or\ v > v^{c}{}_{o} \qquad \text{(II.19)}$$

$$P(v) = P_{rated} \times \frac{v^3 - v^{\mathrm{cI3}}}{v_{\mathrm{r}}{}^3 - v^{\mathrm{cI3}}} \qquad for\ v^{\mathrm{cI}} \leq v < v_{\mathrm{r}} \qquad \text{(II.20)}$$

$$P(v) = P_{rated} \qquad for\ v_{\mathrm{r}} \leq v \leq v^{\mathrm{c}}{}_{\mathrm{o}} \qquad \text{(II.21)}$$

II.5.5. Wind Energy Pre-Sizing:

The annual energy contribution of a wind turbine is estimated using its rated power and capacity factor C^f, which is the ratio of actual annual output to the theoretical maximum at full rated operation, [6]:

$$E_{wind,annual} = P_{rated} \times C_f \times 8760 \qquad \text{(II.22)}$$

- $E_{u}{}^{I}{}_{n}{}^{d}{}_{,annual}$ — Annual energy produced by the wind turbine (kWh/year)
- $P_{rate}{}^{d}$ — Rated turbine power (kW)
- C^f — Capacity factor (dimensionless); typically 0.15 to 0.35 for small onshore turbines at moderate wind sites
- 8760 — Total hours in one year

For the Tlemcen site with an estimated hub-height wind speed of 4.93 m/s at 30 m, a capacity factor of 0.20 to 0.25 is expected. A 20 kW turbine at $C^f = 0.20$ would contribute approximately 35,000 kWh per year, covering around 17% of the station's annual demand of 208,200 kWh. [6]

II.6. Battery Energy Storage System: Modeling and Sizing

II.6.1. Role and Technology Selection

The battery storage bank serves as an energy buffer between intermittent renewable sources and steady loads. When output exceeds demand, the battery absorbs the surplus; but when production falls short means less than the demand, it fills the gap. Correct battery sizing directly influences the system's capacity to sustain supply continuity throughout nighttime hours and multi-day periods of low solar irradiation or calm wind. [12]

Lithium iron phosphate (LFP) technology was chosen for this investigation due to its long cycle life (3,000 to 6,000 complete cycles at 80% depth of discharge), superior thermal stability, low self-discharge rate, and demonstrated dependability in stationary commercial applications. These features make it ideal for the Tlemcen environment, when summer ambient temperatures consistently surpass 35°C. [12]

II.6.2. State of Charge Model:

The State of Charge (SOC) is the fundamental operating variable of the battery, representing the fraction of current stored energy relative to maximum capacity.[13] Its time evolution is governed by the energy balance equation:

$$SOC(t) = SOC(t-1) + \frac{\eta_c \times P_{ch}(t) - \frac{P_{dis}(t)}{\eta_d}}{C_{bat}} \times \Delta t \tag{II.23}$$

- $SOC(t)$ — State of charge at time step t (0 to 1)
- η^c — Charging efficiency; typically 0.95 to 0.99 for LFP
- η^d — Discharging efficiency; typically 0.95 to 0.99 for LFP
- $P^{ch}(t)$ — Charging power at time step t (kW)
- $P^{dI}{}_s(t)$ — Discharging power at time step t (kW)
- Δt — Simulation time step duration (h); 1 hour in PVsyst
- $C^b{}_{at}$ — Nominal battery bank capacity (kWh)

II.6.3. Battery Autonomy and Minimum Capacity

Battery autonomy N_{aut} is the duration the battery can supply the full load without any generation input. [5] It is calculated as:

$$N_{aut} = \frac{C_{bat} \times DOD}{\frac{E_{daily}}{\eta_{inv}}} \tag{II.24}$$

- N_{aut} — Battery autonomy (days)
- $C^b{}_{at}$ — Usable battery capacity (kWh)
- DOD — Maximum allowable depth of discharge; for LFP: 0.80 to 0.90
- $E^d{}_a{}^I{}_l{}^y$ — Average daily energy demand (kWh/day)
- $\eta^I{}_{nv}$ — Inverter efficiency (dimensionless)

The minimum battery capacity required for a given target autonomy is derived directly from this equation, [5]:

$$C_{bat,min} = \frac{N_{aut} \times \frac{E_{daily}}{\eta_{inv}}}{DOD} \qquad \text{(II.25)}$$

II.7. Power Conditioning: Inverter and MPPT Controller:

II.7.1. Inverter Efficiency:

The inverter converts DC power from the PV array and battery into AC power compatible with the station loads. In this hybrid system, a bidirectional inverter-charger manages energy flows in both directions between the DC and AC buses.[14] Its conversion efficiency is:

$$\eta_{inv} = \frac{P_{AC,out}}{P_{DC,in}} \qquad \text{(II.26)}$$

- $P_a{}^c{}_{,out}$ — AC power delivered to the load (W or kW)
- $P^{dc}{}_{,}{}^{I}{}_{n}$ — DC power consumed from the array or battery (W or kW)

The EURO efficiency, which provides a more realistic measure of average inverter performance under partial load conditions, [14] is computed as:

$$\eta_{EURO} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.10\eta_{30\%} + 0.48\eta_{50\%} + 0.20\eta_{100\%} \qquad \text{(II.27)}$$

II.7.2. Inverter Sizing:

The inverter nominal power must accommodate the maximum simultaneous load without saturation. The Aboutachfine station's peak demand is between 60 and 100 kW, hence the inverter must be rated at a minimum of 100 kVA. Using a 10 to 20% safety buffer for inrush currents, power factor, and thermal derating in summer produces a recommended rating of 110 to 120 kVA. [14]

II.8. Energy Management Strategy

The energy management system (EMS) converts the separate components into a coherent and dependable hybrid power station by continually monitoring the state of charge (SOC), generation output, and load demand, and dispatching energy according to a specified priority hierarchy:

First priority — Direct supply of the load from available renewable generation (PV and wind). No battery or generator activation is needed when renewable output meets or exceeds the load.

- Second priority — Battery discharge to cover the deficit when renewable generation is insufficient and SOC is above $SOC_{m}{}^{I}{}_{n}$.[13]

The instantaneous energy balance equation governing this dispatch logic at every time step is:

$$E_{gen}(t) + E_{bat,dis}(t) + E_{backup}(t) = E_{load}(t) + E_{bat,ch}(t) + E_{excess}(t) \qquad \text{(II.28)}$$

- $E^{G}{}_{en}(t)$ — Total renewable energy from PV and wind (kWh)
- $E^{b}{}_{at,}{}^{dI}{}_{s}(t)$ — Energy discharged from battery (kWh)
- $E^{b}{}_{a}{}^{ck}{}_{up}(t)$ — Energy from backup generator (kWh)
- $E_{loa}{}^{d}(t)$ — Energy consumed by loads (kWh)
- $E^{b}{}_{at,}{}^{ch}(t)$ — Energy stored in battery (kWh)
- $E_{ex}{}^{c}{}_{ess}(t)$ — Excess energy that cannot be stored or used (kWh); ideally zero in a well-sized system
- Third priority — Backup generator activation when battery SOC falls below the activation threshold (SOC = 0.15), ensuring uninterrupted supply at all times.
- Fourth priority — Battery charging from surplus renewable energy when the load is fully met and $SOC < SOC_{max}$ (0.96).

The instantaneous energy balance equation governing this dispatch logic at every time step is, [13]:

$$E_{gen}(t) + E_{bat,dis}(t) + E_{backup}(t) = E_{load}(t) + E_{bat,ch}(t) + E_{excess}(t) \qquad \text{(II.29)}$$

- $E^{G}{}_{en}(t)$ — Total renewable energy from PV and wind (kWh)
- $E^{b}{}_{at,}{}^{dI}{}_{s}(t)$ — Energy discharged from battery (kWh)
- $E^{b}{}_{a}{}^{ck}{}_{up}(t)$ — Energy from backup generator (kWh)
- $E_{loa}{}^{d}(t)$ — Energy consumed by loads (kWh)
- $E^{b}{}_{at,}{}^{ch}(t)$ — Energy stored in battery (kWh)
- $E_{ex}{}^{c}{}_{ess}(t)$ — Excess energy that cannot be stored or used (kWh); ideally zero in a well-sized system

II.9. Simulation and Optimization Software:

II.9.1. PVsyst V8.1.2:

A. Definition and Purpose:

PVsyst is a professional photovoltaic simulation software developed at the University of Geneva and currently distributed commercially by PVsyst SA (Satigny, Switzerland). It is one of the most widely used tools in academic research and industrial engineering for the study, sizing, simulation, and energy analysis of photovoltaic systems in three configurations: grid-connected, standalone, and pumping. PVsyst is recognized for its rigorous physical component models, its large validated equipment database, and its transparent loss diagram that identifies every source of energy reduction in the system chain. [15]

B. Simulation Engine and Models:

PVsyst V8.1.2 performs an hourly energy balance simulation over a full year, evaluating the complete energy chain from incident solar radiation to useful energy delivered to the load at every hour.[15] The software implements the following sequence of validated physical models:

- The Perez transposition model converts global horizontal irradiation into effective irradiation on the tilted collector plane, separating direct beam, diffuse sky, and ground-reflected components.
- The one-diode equivalent circuit model governs the I-V characteristic calculation at each time step based on effective irradiance and module operating temperature.
- The thermal model computes module temperature from ambient temperature and irradiance using the thermal loss factor Uc.

- The battery model tracks the SOC at each step using the energy balance equation of Section: State of Charge Model.
- The backup generator model activates when SOC falls below the defined threshold and calculates fuel consumption accordingly. [15]

C. Key Output Indicators:

At the end of the annual simulation, PVsyst produces a complete set of performance indicators including: annual useful energy (E_User), solar fraction (SF), Performance Ratio (PR), specific production (Y_f), backup generator energy and fuel consumption, battery state of wear, and the detailed loss diagram.[15]

II.9.2. HOMER Pro:

A. Definition and Purpose:

HOMER Pro (Hybrid Optimization Model for Electric Renewables) is a simulation and optimization software originally developed by the National Renewable Energy Laboratory (NREL) and currently maintained by UL Solutions. It is specifically designed for the techno-economic analysis and optimization of hybrid power systems combining photovoltaic arrays, wind turbines, diesel generators, hydropower, and battery storage, with or without grid connection. HOMER Pro is widely recognized as the industry standard for hybrid renewable energy system design. [16]

B. Simulation and Optimization Engine:

HOMER Pro simulates a full year of system operation at hourly time steps, evaluating the energy balance at each step based on the user-defined dispatch strategy. Its principal strength is its optimization capability: it evaluates all feasible combinations of component sizes and ranks them by net present cost (NPC) or levelized cost of energy (LCOE).[16] The NPC is defined as:

$$NPC = \frac{C_{ann,tot}}{CRF(i,R\_proj)} \tag{II.30}$$

- $C_{ann,tot}$ — Total annualized system cost including capital, replacement, O&M, and fuel costs (USD/year)
- CRF(i, R_{pro}^{i}) — Capital recovery factor; function of annual discount rate i and project lifetime R_{pro}^{i} in years

The LCOE, expressing average cost per unit of useful energy served, is:

$$LCOE \; = \frac{NPC \times CRF}{E_{served,annual}} \qquad \text{(II.31)}$$

- $E_{serve}{}^{d}{}_{,annual}$ — Total annual energy served to the load (kWh/year)

II.10. PV Array Configuration and Simulation Setup:

II.10.1. Module Selection and Array Configuration:

Based on the analytical pre-sizing result of approximately 68.4 kWp and the available commercial module options, the Jinko Solar JKM-72HC-BDVP-550M monocrystalline bifacial half-cell module was selected for this study. With a rated power of 550 Wp per module under STC conditions, a total of 112 modules are required to achieve the target array power. These modules are arranged in the PVsyst simulation environment as 14 strings of 8 modules connected in series, giving a total nominal peak power of 61.6 kWp. [15]

Applying the array configuration equations established in Section: Photovoltaic System: Modeling and Sizing (Equations II.9 to II.11), the array-level operating quantities at STC are: $V_{arra}{}^{y} = 8 \times V_{mo}{}^{d}{}_{ule}$, $I_{arra}{}^{y} = 14 \times I_{mo}{}^{d}{}_{ule}$, and $P_{arra}{}^{y} = 112 \times 550 = 61{,}600$ Wp = 61.6 kWp. The array is controlled through an MPPT converter with a peak efficiency of 98.0% and a European weighted efficiency of 96.5%.[15]

Parameter	Value	Source / Standard
Module Model	JKM-72HC-BDVP-550M	Jinko Solar datasheet
Module Nominal Power	550 Wp	STC: 1000 W/m², 25°C
Number of Modules	112 units	14 strings × 8 in series
Total Array Peak Power	61.6 kWp	PVsyst V8.1.2
Array Orientation	Tilt: 35° / Azimuth: 0° (South)	PVsyst optimization

Module Area	289 m² total	112 × 2.58 m²
MPPT Peak Efficiency	98.0%	PVsyst input
EURO Efficiency	96.5%	PVsyst input
Thermal Loss Factor Uc	20.0 W/m²K	PVsyst default — free-standing
Meteorological Data Source	Meteonorm 9.0 (Satellite 100%)	Tlemcen, lat. 34.88°N

Table II.1: PV array configuration and simulation input parameters (Source: PVsyst V8.1.2) [15]

II.10.2. Battery Bank Configuration

The battery storage system configured in PVsyst consists of 600 LFP units (lithium iron phosphate), arranged as 60 parallel groups of 10 cells in series. This configuration yields a nominal bank voltage of 256 V and a total nominal capacity of 10,800 Ah, corresponding to a stored energy of 2,488.3 kWh. The battery management control thresholds were set as follows: SOC charging upper limit = 0.96, SOC discharging lower limit = 0.10, and backup generator activation threshold = 0.15. These parameters are directly referenced in Equation II.23 of Section: State of Charge Model.[15]

II.11. Summary of Design Parameters and Governing Equations

The following table consolidates all principal design parameters of the hybrid system as determined by the analytical pre-sizing methodology and simulation configuration established in this chapter. These values constitute the reference inputs for the PVsyst and HOMER Pro simulations presented in Chapter III.

Component / Parameter	Value	Governing Equation
PV Array Peak Power	61.6 kWp	Eq. II.12– II.13
Number of Modules	112 (14×8)	Eq. II.9– II.11
Module Model	JKM-72HC-BDVP-550M, 550 Wp	Section II.10
Array Orientation	35° tilt, 0° azimuth	PVsyst optimization
Wind Turbine Rated Power	20 kW (proposed)	Eq. II.14, II.22
Hub Height	30 m	Eq. II.17 – II.18
Wind Speed at Hub Height	≈4.93 m/s	Eq. II.18
Battery Technology	Lithium-ion LFP	Section: Role and Technology Selection
Battery Nominal Capacity	2,488 kWh	Eq. II.23 – II.25
Battery Configuration	60 parallel × 10 series	PVsyst V8.1.2
Inverter Peak Efficiency	98.0%	Eq. II.26
Target Solar Fraction	50%	Eq. II.12
Daily Energy Demand	≈580 kWh/day	Load profile analysis
Annual Energy Demand	≈208,200 kWh/year	Load profile analysis

Table II.2: Summary of hybrid system design parameters and associated governing equations [15]

II.12. Conclusion:

This chapter provides the whole theoretical and methodological underpinning for designing, simulating, and evaluating the hybrid photovoltaic-wind energy system proposed for the Aboutachfine service station. It has done so in an organized and academically logical order: theoretical models and equations first, then software tools, and last particular simulation settings.

For the photovoltaic subsystem, the one-diode model (Equation II.3) and its temperature correction equations (II.4 and II.5) explain the physical behaviour of the solar cell under the Tlemcen site's varied climatic circumstances. The Performance Ratio (Equation II.10) and Specific Production (Equation II.11) define the standardized metrics for evaluating the PVsyst findings in Chapter III. The analytical pre-sizing (Equation II.12) produced an estimate of 68.4 kWp, which is consistent with the final simulated design of 61.6 kWp.

For the wind turbine, the kinetic power law (Equation II.14), Betz limit (Equation II.15), Hellmann height correction (Equation II.17), and piecewise power curve (Equations II.19-21) work together to show how the corrected hub-height wind speed of 4.93 m/s at 30 m translates into a viable complementary contribution to the PV array. The battery's SOC equation (II.23) and autonomy calculation (II.24) give a foundation for analyzing the 2,488 kWh LFP bank established in PVsyst. The energy management balance equation (II.28) formalizes the system's priority dispatch logic for each time step.

PVsyst V8.1.2 and HOMER Pro have been completely defined, their functions are obvious, and the PV array layout and battery setup are extensively stated in Section II.5.3, Chapter III may now present and analyze simulation results with complete scientific transparency and traceability to the models and parameters provided here.

Bibiography

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Chapter III:

Results and Interpretation

I. Introduction

This section shows and examines the findings from the modelling and optimization of the planned renewable energy systems for the Aboutachfine service station. The performance of the independent photovoltaic system modelled using PVsyst is first assessed and compared to that of the hybrid PV-Wind system optimized with HOMER Pro. The examination concentrates on essential technical, environmental, and economic parameters, such as energy generation, renewable portion, fuel consumption, and system dependability. Furthermore, the impact of integrating wind energy into the current photovoltaic arrangement is evaluated in terms of energy autonomy, reduced operational costs, and environmental advantages. The obtained results give a solid foundation for determining the best appropriate energy solution for the study site.

We used the Aboutachfine fuel service station in Tlemcen as the simulation case. Its average consumption is 17,350 kWh/month, which corresponds to an annual consumption of about 208,000 kWh/year. The following is an indicative sizing for a solar-wind hybrid mini-power plant adapted to this load profile:

- Daily average: 17,350 / 30 ≈ 580 kWh/day [1]
- Average continuous power: 580 / 24 ≈ 24 Kw [1]

II. Service Station Sizing

II.1. Solar Sizing (PV) :

- Average irradiation in Tlemcen is about 5 kWh/kWp/day. [3]
- Target requirement: cover about 50% of the consumption (≈ 290 kWh/day).
- Required PV power: 290 / 5 ≈ 58 kWp
- Required area: ~7 m²/kWp → ≈ 400 m² of roof or ground space.
- Annual production: ~105,000 kWh/year.

II.2. Wind Sizing:

- Assumed average wind speed: 4 m/s (non-exposed site). [3]
- A small 20 kW wind turbine will produce around 30–40 MWh/year (≈ 15–20% of the demand).
- If the site is windy (≥ 6 m/s), a 30 kW machine can exceed 60 MWh/year. [3]

II.3. Battery Storage:

- Objective: night autonomy and smoothing.

A. Scenarios:

- 4 h autonomy: 24 kW × 4 h ≈ 100 kWh.
- 12 h autonomy: ≈ 300 kWh.
- 24 h autonomy: ≈ 600 kWh.

- Realistic choice: 200–300 kWh to cover the night and peak periods.

B. Simplified electrical scheme:

- PV → inverter → AC panel.
- Wind → controller → AC inverter.
- Battery → bidirectional inverter (storage / discharge).
- Priority: critical loads (pumps, refrigeration, lighting).
- Grid connection: backup + possible surplus injection.

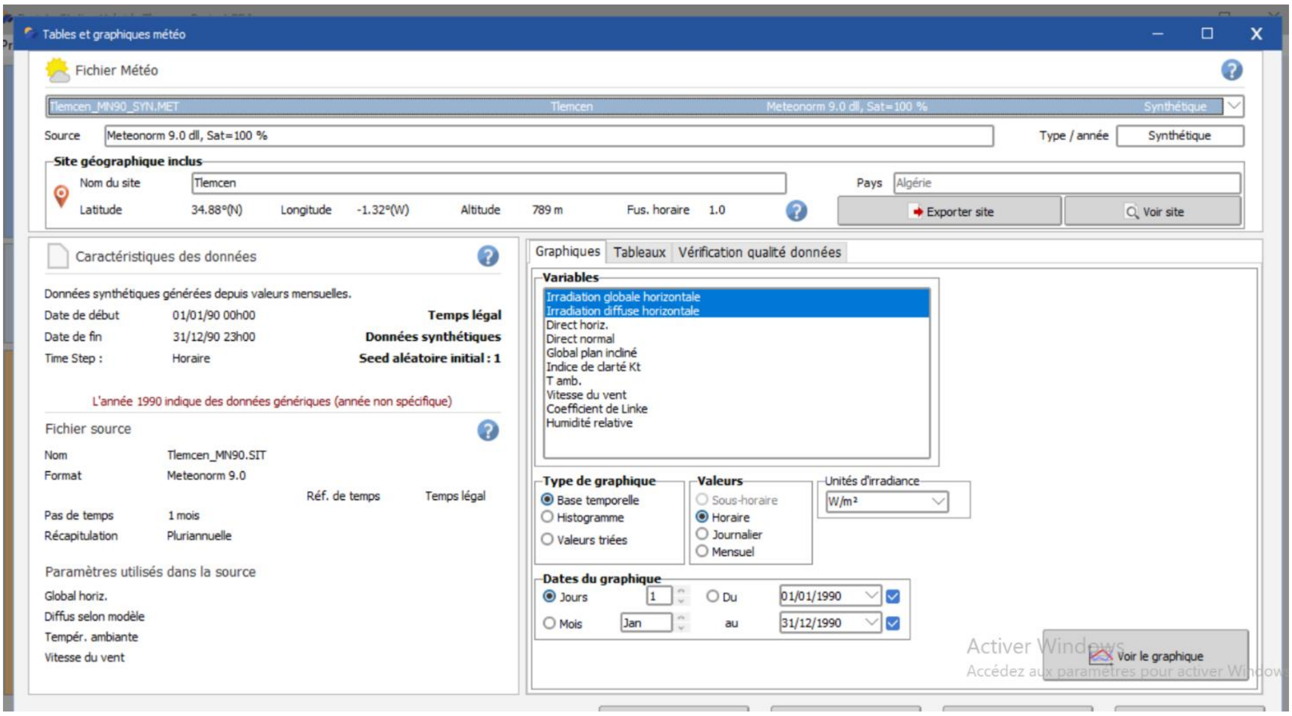
C. Next steps:

1. Check the real hourly profile (day/night, peaks).
2. Measure the local wind (anemometer over 6–12 months).
3. Study the available PV area and installation constraints.
4. Adjust sizing according to the objective (full autonomy or bill reduction).

II.4. Investment estimate:

- PV 60 kWc: ~ 7 000 000 - 9 500 000 Dinar algérien (115 000 - 250 000 Dinars algerien / kWc).
- Wind 20 kW: ~ 7 500 000 - 10 000 000 Dinar algérien.
- batteries 250 kWh Li-ion: ~15 000 000 - 25 000 000 Dinar algérien.
- Total indicatif: 29 500 000 - 44 500 000 Dinar algérien.
- savings annual (50% autoconsumption): ~ 2 350 000 - 3 100 000 Dinar algérien.

III. Design of the PV + Battery + Grid System



Tables et graphiques météo

Fichier Météo

Tlemcen_MN90_SYN.MET Tlemcen Meteonorm 9.0 dll, Sat=100 % Synthétique

Source: Meteonorm 9.0 dll, Sat=100 %

Type / année: Synthétique

Site géographique inclus

Nom du site: Tlemcen

Pays: Algérie

Latitude 34.88°(N) Longitude -1.32°(W) Altitude 789 m Fus. horaire 1.0

Caractéristiques des données

Données synthétiques générées depuis valeurs mensuelles.

Date de début	01/01/90 00h00	**Temps légal**
Date de fin	31/12/90 23h00	**Données synthétiques**
Time Step :	Horaire	**Seed aléatoire initial : 1**

L'année 1990 indique des données génériques (année non spécifique)

Fichier source

Nom: Tlemcen_MN90.SIT

Format: Meteonorm 9.0

Réf. de temps: Temps légal

Pas de temps: 1 mois

Récapitulation: Pluriannuelle

Paramètres utilisés dans la source

Global horiz.

Diffus selon modèle

Tempér. ambiante

Vitesse du vent

Variables

- Irradiation globale horizontale
- Irradiation diffuse horizontale
- Direct horiz.
- Direct normal
- Global plan incliné
- Indice de clarté Kt
- T amb.
- Vitesse du vent
- Coefficient de Linke
- Humidité relative

Type de graphique

- ● Base temporelle
- ○ Histogramme
- ○ Valeurs triées

Valeurs

- ○ Sous-horaire
- ● Horaire
- ○ Journalier
- ○ Mensuel

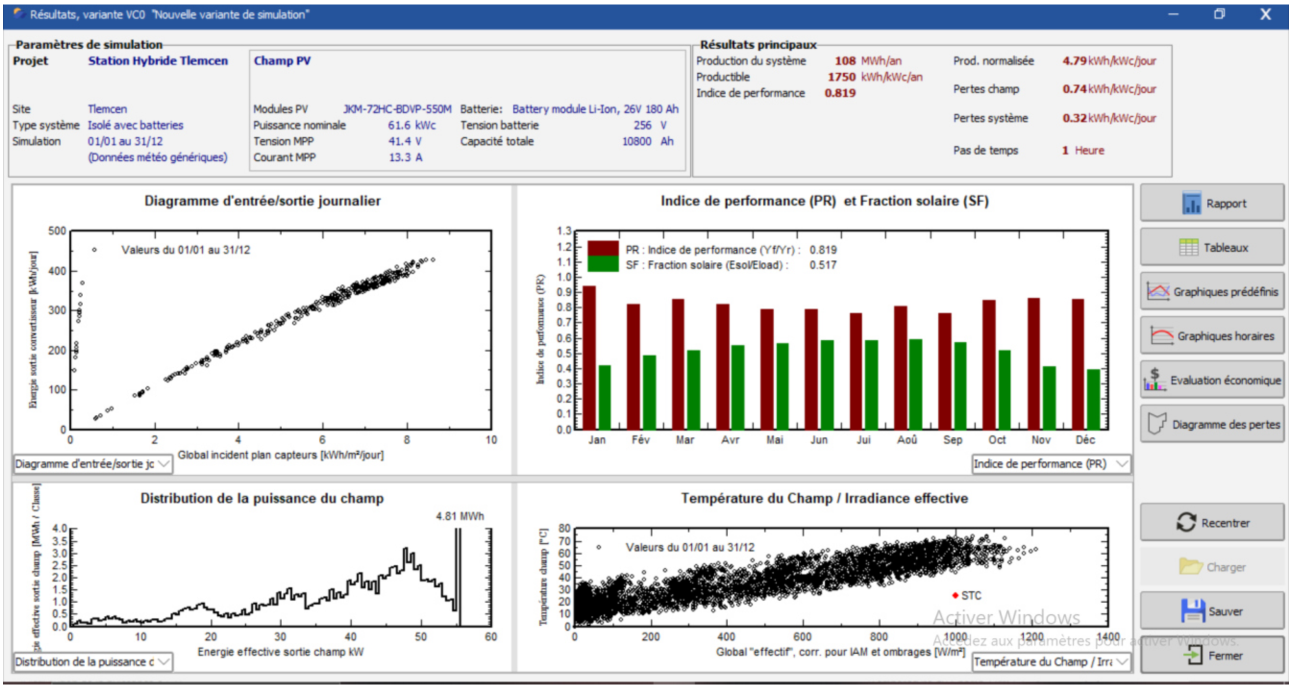
Unités d'irradiance: W/m²

Dates du graphique

● Jours 1 ○ Du 01/01/1990 ☑

○ Mois Jan au 31/12/1990 ☑

Figure III.1: Weather Tables and Graphics



Résultats, variante VC0 "Nouvelle variante de simulation"

Paramètres de simulation

Projet: **Station Hybride Tlemcen**

Site: Tlemcen

Type système: Isolé avec batteries

Simulation: 01/01 au 31/12 (Données météo génériques)

Champ PV

Modules PV: JKM-72HC-BDVP-550M

Puissance nominale: 61.6 kWc

Tension MPP: 41.4 V

Courant MPP: 13.3 A

Batterie: Battery module Li-Ion, 26V 180 Ah

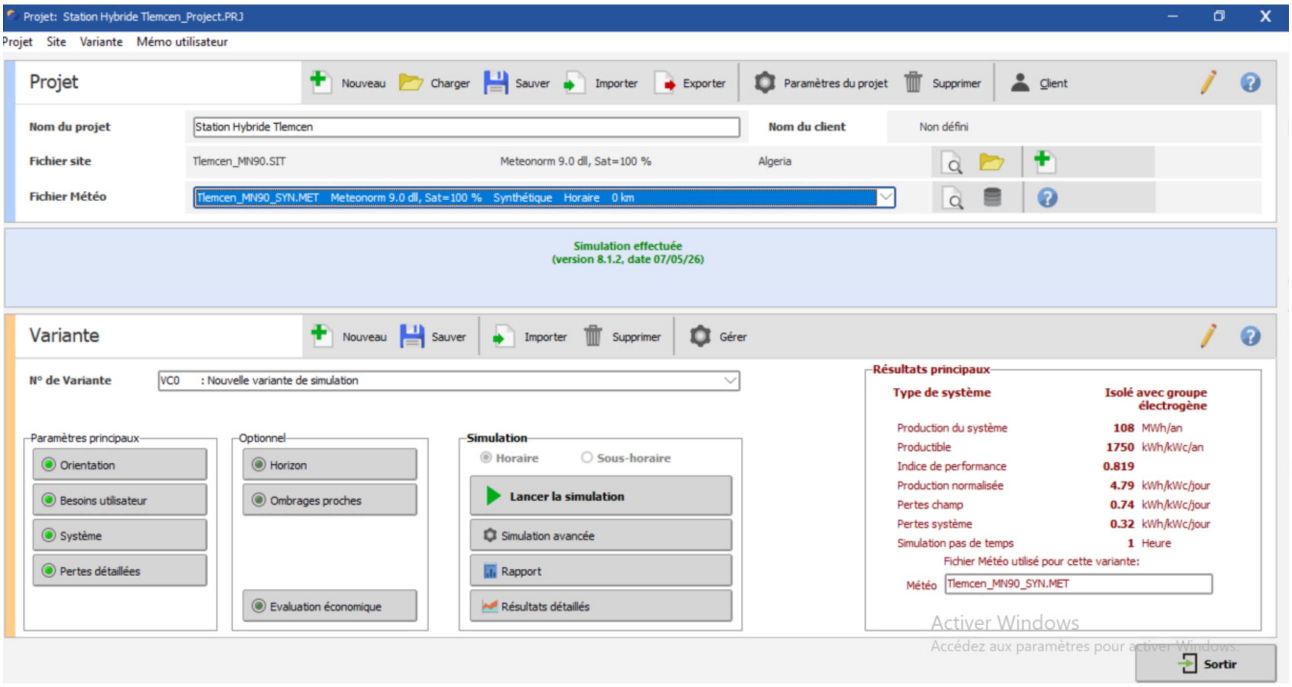
Tension batterie: 256 V

Capacité totale: 10800 Ah

Résultats principaux

Production du système	**108** MWh/an	Prod. normalisée	**4.79** kWh/kWc/jour
Productible	**1750** kWh/kWc/an	Pertes champ	**0.74** kWh/kWc/jour
Indice de performance	**0.819**	Pertes système	**0.32** kWh/kWc/jour
		Pas de temps	**1** Heure

Figure III.2 : Results, Variant VC0 New Simulation Variant



Nom du projet: Station Hybride Tlemcen

Nom du client: Non défini

Fichier site: Tlemcen_MN90.SIT Meteonorm 9.0 dll, Sat=100 % Algeria

Fichier Météo: Tlemcen_MN90_SYN.MET Meteonorm 9.0 dll, Sat=100 % Synthétique Horaire 0 km

Simulation effectuée
(version 8.1.2, date 07/05/26)

N° de Variante: VC0 : Nouvelle variante de simulation

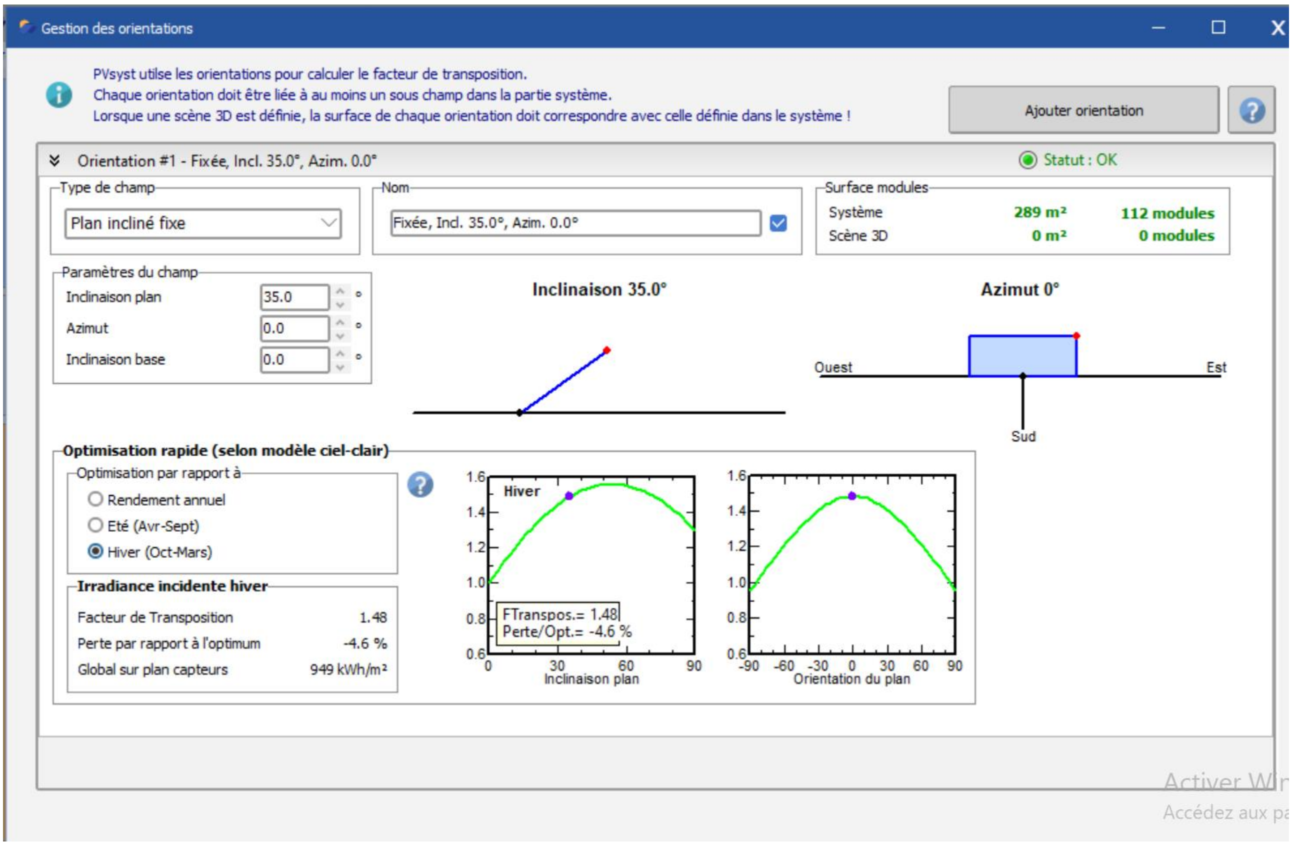
Résultats principaux

Type de système	Isolé avec groupe électrogène	
Production du système	108	MWh/an
Productible	1750	kWh/kWc/an
Indice de performance	0.819	
Production normalisée	4.79	kWh/kWc/jour
Pertes champ	0.74	kWh/kWc/jour
Pertes système	0.32	kWh/kWc/jour
Simulation pas de temps	1	Heure

Fichier Météo utilisé pour cette variante:

Météo: Tlemcen_MN90_SYN.MET

Figure III.3: Project: Station_Hybride_Tlemcen_Project.PRJ



PVsyst utilse les orientations pour calculer le facteur de transposition.
Chaque orientation doit être liée à au moins un sous champ dans la partie système.
Lorsque une scène 3D est définie, la surface de chaque orientation doit correspondre avec celle définie dans le système !

Orientation #1 - Fixée, Incl. 35.0°, Azim. 0.0° Statut : OK

Type de champ: Plan incliné fixe

Nom: Fixée, Incl. 35.0°, Azim. 0.0° ☑

Surface modules

Système	289 m²	112 modules
Scène 3D	0 m²	0 modules

Paramètres du champ
Inclinaison plan 35.0 °
Azimut 0.0 °
Inclinaison base 0.0 °

Optimisation rapide (selon modèle ciel-clair)

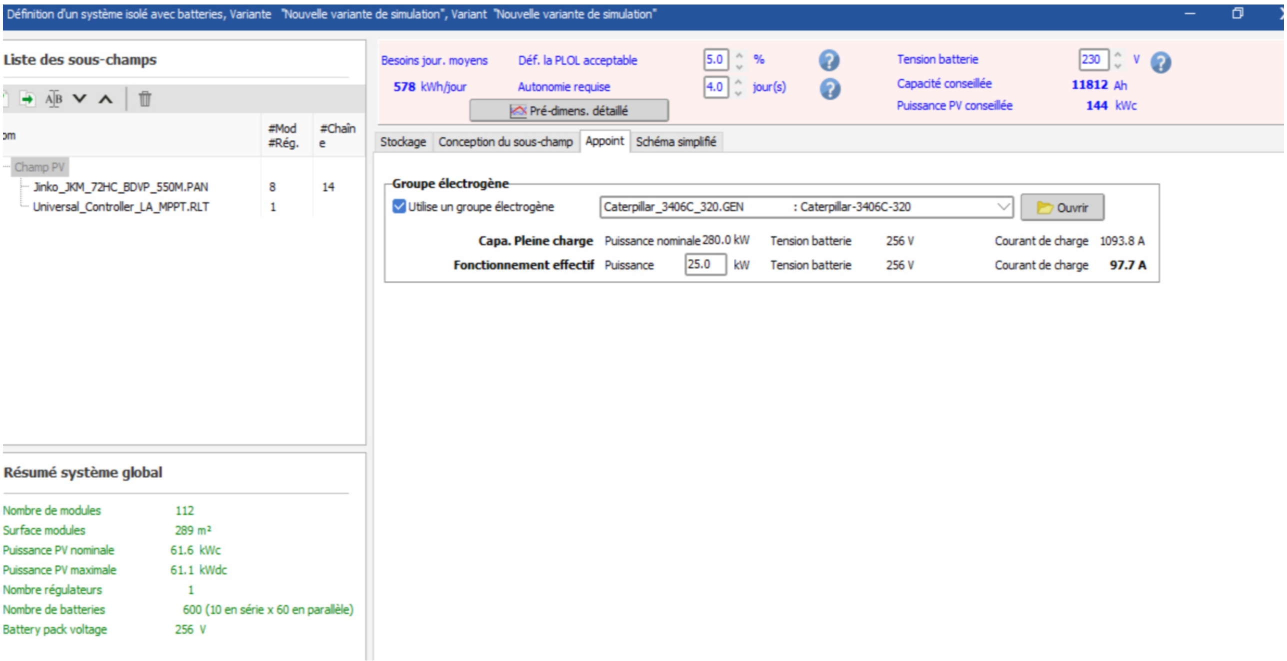
Optimisation par rapport à
○ Rendement annuel
○ Eté (Avr-Sept)
● Hiver (Oct-Mars)

Irradiance incidente hiver

Facteur de Transposition	1.48
Perte par rapport à l'optimum	-4.6 %
Global sur plan capteurs	949 kWh/m²

FTranspos.= 1.48
Perte/Opt.= -4.6 %

Figure III.4: Orientation Management



Définition d'un système isolé avec batteries, Variante "Nouvelle variante de simulation", Variant "Nouvelle variante de simulation"

Liste des sous-champs

om	#Mod #Rég.	#Chaîne
Champ PV		
Jinko_JKM_72HC_BDVP_550M.PAN	8	14
Universal_Controller_LA_MPPT.RLT	1	

Besoins jour. moyens 578 kWh/jour
Déf. la PLOL acceptable 5.0 %
Autonomie requise 4.0 jour(s)
Tension batterie 230 V
Capacité conseillée 11812 Ah
Puissance PV conseillée 144 kWc

Groupe électrogène

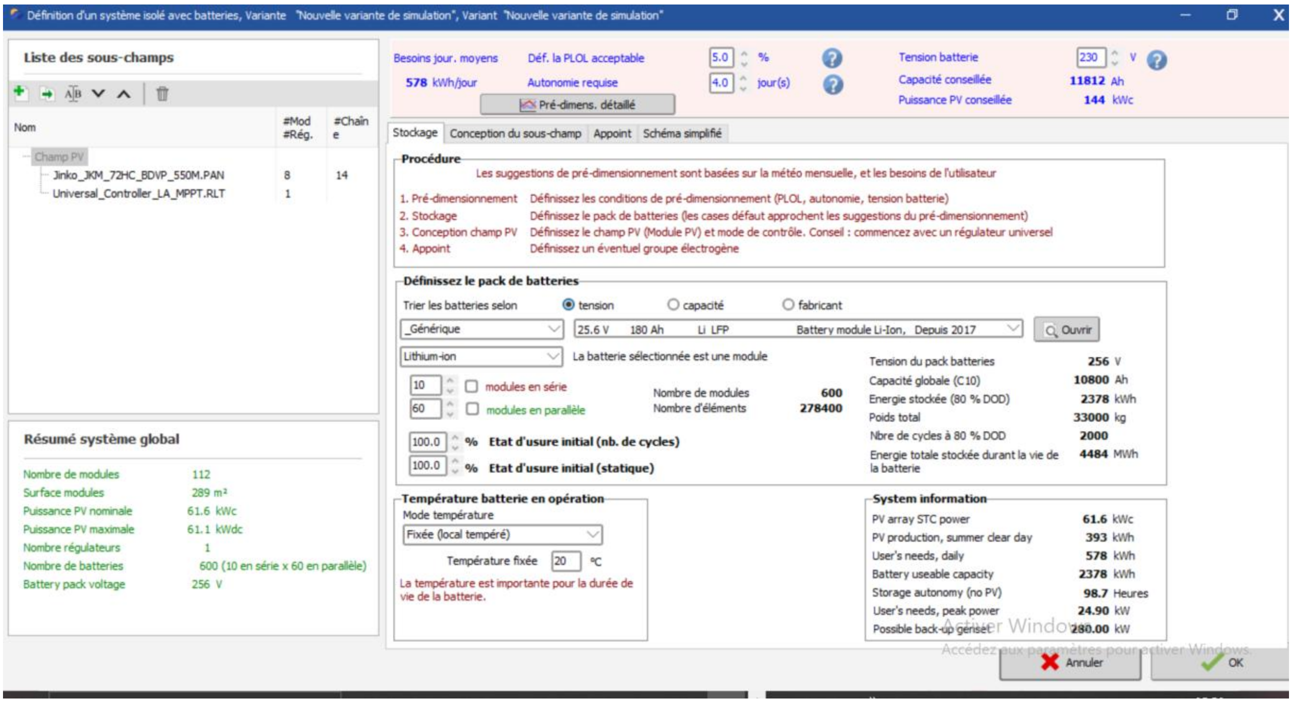
☑ Utilise un groupe électrogène: Caterpillar_3406C_320.GEN : Caterpillar-3406C-320

Capa. Pleine charge Puissance nominale 280.0 kW Tension batterie 256 V Courant de charge 1093.8 A
Fonctionnement effectif Puissance 25.0 kW Tension batterie 256 V Courant de charge **97.7 A**

Résumé système global

Nombre de modules	112
Surface modules	289 m²
Puissance PV nominale	61.6 kWc
Puissance PV maximale	61.1 kWdc
Nombre régulateurs	1
Nombre de batteries	600 (10 en série x 60 en parallèle)
Battery pack voltage	256 V

Figure III.5: Definition of an isolated system with batteries, Variant VC0



Définition d'un système isolé avec batteries, Variante "Nouvelle variante de simulation", Variant "Nouvelle variante de simulation"

Liste des sous-champs

Nom	#Mod #Rég.	#Chaîne
Champ PV		
Jinko_JKM_72HC_BDVP_550M.PAN	8	14
Universal_Controller_LA_MPPT.RLT	1	

Besoins jour. moyens 578 kWh/jour
Déf. la PLOL acceptable 5.0 %
Autonomie requise 4.0 jour(s)
Tension batterie 230 V
Capacité conseillée 11812 Ah
Puissance PV conseillée 144 kWc

Procédure

Les suggestions de pré-dimensionnement sont basées sur la météo mensuelle, et les besoins de l'utilisateur

1. Pré-dimensionnement	Définissez les conditions de pré-dimensionnement (PLOL, autonomie, tension batterie)
2. Stockage	Définissez le pack de batteries (les cases défaut approchent les suggestions du pré-dimensionnement)
3. Conception champ PV	Définissez le champ PV (Module PV) et mode de contrôle. Conseil : commencez avec un régulateur universel
4. Appoint	Définissez un éventuel groupe électrogène

Définissez le pack de batteries

Trier les batteries selon ● tension ○ capacité ○ fabricant

_Générique — 25.6 V 180 Ah Li LFP Battery module Li-Ion, Depuis 2017

Lithium-ion — La batterie sélectionnée est une module

10 ☐ modules en série
60 ☐ modules en parallèle

Nombre de modules 600
Nombre d'éléments 278400

100.0 % **Etat d'usure initial (nb. de cycles)**
100.0 % **Etat d'usure initial (statique)**

Tension du pack batteries	256 V
Capacité globale (C10)	10800 Ah
Energie stockée (80 % DOD)	2378 kWh
Poids total	33000 kg
Nbre de cycles à 80 % DOD	2000
Energie totale stockée durant la vie de la batterie	4484 MWh

Température batterie en opération

Mode température: Fixée (local tempéré)
Température fixée 20 °C

La température est importante pour la durée de vie de la batterie.

System information

PV array STC power	61.6 kWc
PV production, summer clear day	393 kWh
User's needs, daily	578 kWh
Battery useable capacity	2378 kWh
Storage autonomy (no PV)	98.7 Heures
User's needs, peak power	24.90 kW
Possible back-up genset	280.00 kW

Résumé système global

Nombre de modules	112
Surface modules	289 m²
Puissance PV nominale	61.6 kWc
Puissance PV maximale	61.1 kWdc
Nombre régulateurs	1
Nombre de batteries	600 (10 en série x 60 en parallèle)
Battery pack voltage	256 V

Figure III.6: Definition of an isolated system with batteries - Battery pack selection

- Installed PV power: 61.6 kWp (112 modules Jinko 550 Wp, total area 289 m²).
- Orientation: tilt 35°, azimuth 0° (due south).
- Storage: Lithium-ion LFP battery bank, consisting of 600 units (10 in series × 60 in parallel), with a nominal voltage of 256 V and a capacity of 10,800 Ah, providing approximately 2,488 kWh of usable energy.
- Diesel generator: backup Caterpillar 280 kW, used to compensate for the solar deficit.
- Average daily demand: ~578 kWh/day.

IV. Production and performance :

- Useful solar energy: 111 433 kWh/an.
- Total energy supplied to the consumer (PV + generator): 211 092 kWh/an.
- Specific yield: 1 750 kWh/kWp/an → a high value, consistent with the sunshine level in Tlemcen.
- Performance Ratio (PR): 81.9 % → very good overall system efficiency.
- Solar fraction (SF): 51.7% → about half of the demand is covered by solar power, while the rest is supplied by the diesel generator.

IV.1. Batteries and energy management

- Theoretical autonomy: ~ 4 jours sans soleil (≈ 2 378 kWh utilisables à 80% DOD).
- • SOC (State of Charge): well-defined thresholds for charge/discharge control and generator start-up.
- Estimated lifetime: 2000 cycles à 80% DOD → ≈ 5 - 6 ans en usage intensif.

IV.2. Diesel generator:

- Energy supplied: 103 295 kWh/an.
- Fuel consumption: 289 227 L/an → impact economic et environnemental significatif.
- Role: ensures service continuity, but accounts for nearly half of the total supply.

IV.3. Identified losses:

- PV field losses: 0.74 kWh/kWp/jour (≈ 15 %).
- System losses (conversion, battery): 0.32 kWh/kWp/jour (≈ 7 %).

- **Main causes:**
  - **Module temperature losses (≈ −7.8%).**
  - **Mismatch and wiring losses (≈ −2–3%).**
  - **Converter efficiency losses (≈ −2%).**

IV.4. Monthly analysis:

- Best periods: mai-août (SF > 0.58, PR stable).
- • Critical periods: November–February (SF < 0.45, heavy reliance on the generator).
- Example: in December, the solar fraction drops to 39%, with 11,077 kWh supplied by the generator.

V.Overall interpretation:

- The system is appropriately scaledfor an isolated site, with a high PR and solar coverage over 50%.
- The diesel generator accounts for about 49% of total energy, leading to substantial fuel consumption.
- The batteries give excellent autonomy, they need to be replaced periodically.

To improve the solar fraction and reduce costs/carbon emissions:

- Increase installed PV capacity to 100-120 kWp.
- Optimize battery charge and discharge control.
- Consider a hybrid coupling with wind or the grid.

In conclusion, the simulation demonstrates a durable system, although it remains overly reliant on diesel. Solar power covers about half of the demand efficiently, with a high yield, but more PV growth or hybridization would be required to move toward to progress toward autonomy and minimize the economic and environmental impact.

VI. Financial aspect of the installation:

Currently in Algeria, diesel costs approximately 31 DZD/L (≈ \$0.24/L), resulting in a yearly use of 289,227 L by the diesel generator, equivalent to nearly 9 million DZD (approximately \$65,000). In instance, increasing the PV array from 61.6 kWp to 120 kWp would cost between 24 and 36 million DZD. However, such an update may cut diesel dependency by 50% and allow the investment to be repaid in less than five years through fuel savings, government incentives, and tax breaks.

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💰 Current diesel cost:

- Official price in 2026: 31 DZD/L (≈0.24 \$/L).

- Annual generator consumption: 289,227 L/year.
- Annual cost: ≈ 8.96 million DZD (~65,000 $).
- Environmental impact: ~770 tonnes of CO_2/year (factor 2.67 kg CO_2/L diesel).

⚡ Cost of PV expansion:

- 400 Wp PV panel price: approximately 15,000–25,000 DZD (€90–150) per module.
- Complete 3 kWp PV system installation: approximately 600,000–900,000 DZD.
- Estimated cost for an additional 60 kWp of PV capacity: approximately 12–18 million DZD.
- Expansion to a total installed capacity of 120 kWp: approximately 24–36 million DZD.
- Expected lifetime of PV modules: 25–30 years, with relatively stable performance over time.
- Battery storage: represents the major investment cost; a 48 V, 100 Ah lithium-ion battery typically costs around 200,000–350,000 DZD per unit.

📉 Economic comparison:

Option	Initial investment	Annual expenses	5-year horizon	10-year horizon
Keep diesel	Low (generator already installed)	~9 M DZD/an	45 M DZD	90 M DZD
PV + Battery expansion	24–36 M DZD	<2 M DZD/year (maintenance)	Payback in 4–5 years	Net savings > 50 M DZD

Table III.1: Economic comparison between keeping the diesel generator and expanding the PV system with batteries

🏛 Subsidies and incentives (2026 Finance Law):

- VAT exemption on solar and battery equipment until 2026.
- Reduction of customs duties to 5% for inputs intended for solar panel manufacturing.
- Tax deduction: up to 5% of taxable profit for renewable energy investments.
- National program: 15 GW solar target by 2035, with support for off-grid projects.

• Strategic interpretation:

- Today: diesel covers about 49% of the needs, but it is expensive and polluting.
- With PV expansion, the solar fraction could exceed 80%, reducing diesel consumption by half.
- Profitability: the PV investment is paid back in less than 5 years, with net benefits starting in year 6.
- Environnement: réduction de 400 - 500 tonnes CO_2/an.

VII. Design of the Hybrid PV + Wind + Battery System

Designing a hybrid PV + wind + battery service station with automated EMS and fuel monitoring will reduce diesel dependence (currently ≈ 50%) and significantly lower operating costs in Tlemcen.

- Key Excerpts from the Report. [1]
- "Available solar energy: 111433 kWh/year"
- "Solar Fraction SF: 51.68%"

VII.1. Objective and local constraints:

- Average daily load: ≈ 578 kWh/day (PVsyst data).
- • Existing PV: 61.6 kWp; usable battery storage ≈ 2,378 kWh (80% DOD); diesel supplied ≈ 103,295 kWh/year. These values guide the sizing of the PV and wind complement. [1]

VII.2. Proposed Architecture (Functional Diagram):

- • Sources: existing 61.6 kWp PV + proposed wind 30–60 kW (1–2 medium 30 kW turbines) + diesel generator as backup.
- storage: batteries Li-ion utilisables 2.4 MWh (conserver/optimiser existant) + prévoir capacité additionnelle 1-2 MWh si objectif SF>80%.
- Converters: a central hybrid inverter + MPPT charge controllers for PV; wind controller (rectifier + power controller).
- • Control system (EMS/SCADA): a central supervisor that manages priorities (PV → batteries → wind → diesel), charge/discharge strategy based on SOC, weather forecasts, and fuel prices.
- Fuel monitoring: tank level sensors (ultrasonic), fuel-line flow meters, GSM/ethernet telemetry, and automatic alerts (low threshold, leak, abnormal consumption).

VII.3. Proposed architecture (functional diagram):

- Goal: reduce diesel by about 50% → target SF ≈ 80%.

- **Conservative option:** add **120 kWp of PV capacity, 60 kW of wind power, or a hybrid combination of 60 kWp PV and 30 kW wind,** together with an additional **1–2 MWh of battery storage.**
- **Rationale**: the PV system primarily supplies energy during daytime hours, while the wind system contributes generation during nighttime periods and cloudy conditions. The battery bank smooths power fluctuations, stores excess renewable energy, and reduces the operating hours and cycling frequency of the diesel generator. Detailed sizing methodologies for such hybrid systems are available in microgrid design and planning guides.

VII.4. EMS and Control Logic:

- • Priorities: PV → charge batteries (if SOC < upper threshold) → supply the load → wind injects power as available → diesel starts if SOC < 15% or demand peaks.
- **Algorithms**: solar irradiance and wind speed forecasting (**24–72 hours ahead)** to optimize diesel generator scheduling and minimize start-ups, fuel cost optimization, and intelligent battery cycle management to extend battery service life.
- **Interfaces:** web-based **SCADA** system with real-time monitoring, historical data logging, SMS and email alarm notifications, and API connectivity for billing, reporting, and energy management applications.
-

VIII. Fuel Monitoring:

- Sensors: ultrasonic fuel tank level sensor, fuel flow meter, temperature sensor, and engine vibration sensor.
- Functions: leak detection, hourly consumption tracking, threshold alerts, report of consumption versus renewable production, and start-up lockout in case of anomaly.

VIII.1. Costs, Risks, and Priorities:

- • Estimated costs: 30 kW turbines vary by supplier; additional PV and batteries are more expensive but can be amortized by diesel savings (see the previous economic analysis).
- Risks: wind variability, electrical integration (harmonics), turbine maintenance, and fuel safety.

IX. Recommended operational steps:

1. Mesure sur site : anémomètre 12 mois + vérif. irradiation (confirmer Meteonorm).
2. Detailed feasibility study (HOMER/PVsyst + EMS optimization).

3. Prototype: installer 30 kW wind + 100 kWp PV pilote + EMS, 6-12 mois test.
4. Full deployment and integration of fuel monitoring + SCADA.

X.Complete Ready-to-Deploy Design:

We propose a hybrid PV + wind + battery + diesel station with automated EMS/SCADA and integrated fuel monitoring; the mixed option (≈ +60–120 kWp PV + 30–60 kW wind + 1–2 MWh battery) aims for SF ≈ 75–85% and strongly reduces diesel consumption and operating costs.

9. Quick guide — key decisions and input data:

- Average load: 578 kWh/day (your simulation).
- Existing PV: 61.6 kWp, usable batteries ≈ 2.38 MWh (80% DOD).
- Objectif: Increase the Solar Fraction (SF). 75-85 %, Reduce diesel consumption ≥ 50%.

XI. Technical design :

- Energy sources**:** existing 61.6 kWp PV system, supplemented by an additional 60–120 kWp of PV capacity and/or 30–60 kW of wind power (or a hybrid combination of both renewable sources). [1]
- Energy storage: retain the existing battery bank with a capacity of approximately 2.38 MWh, and add 1–2 MWh of lithium-ion storage depending on the targeted Solar Fraction (SF) and system autonomy requirements. [1]
- Inverters / controllers: a central hybrid inverter (capacity ≥ peak load of 30 kW) + MPPT for PV + wind controller.
- Diesel generator: kept as backup, with automatic start based on SOC and weather forecasts.
- EMS / SCADA: priority dispatch strategy PV → batteries → wind → diesel; 24–72 h irradiance and wind forecasting; cost–fuel optimization algorithms; and a web-based interface with SMS/email alert notifications. [1]

XII. Comparison of options:

Criterion	PV-heavy	PV + Wind Mix
Additional PV	+120 kWp	+60 kWp
Additional wind	0 kW	30-60 kW
Additional battery	+1-2 MWh	+1 MWh
Expected SF	80-90 %	75-85 %
Indicative CAPEX	High	Medium

Table III.2: Comparison of autonomy scenarios for the hybrid station

XIII. EMS logic and key algorithms:

- Optimization: rule-based and forecast-driven algorithms (supported by tools such as HOMER, PVsyst, and HIL simulations) to minimize Cost of Energy (COE) and Loss of Power Supply Probability (LPSP), with multi-objective optimization approaches recommended for system sizing and performance trade-offs. [1]

13. Fuel monitoring — specifications

- Functions: low-threshold alerts, leak detection, start-up lockout, hourly/daily reports, and an API for billing.
- Communication: 4G + redondance (satellite backup if required).

XIV. step deployment plan:

1. Site measurements: 12-month anemometry + irradiation verification.
2. Detailed study: HOMER/PVsyst modeling, EMS optimization.
3. Prototype: installer 30 kW wind + 60-100 kWp PV pilote + EMS (6-12 mois).
4. EMS tests & tuning: validate battery cycles and diesel start strategy.
5. Full deployment: installation of PV/WT/batteries, SCADA integration.
6. Operations & maintenance: O&M contract, fuel monitoring, monthly KPIs.

15. Risks and mitigations

- Wind variability → 12-month anemometry.
- Battery cost → optimize cycles, limit DOD.
- Electrical integration → harmonic study and protection devices.
- • Recommendation: use multi-objective optimization (COE vs LPSP) to finalize the sizing.

16. Complete costed design of the hybrid service station:

Here is a complete costed design of the hybrid PV-wind-diesel service station with batteries, automated EMS, and fuel monitoring.

XIV.1. Overall sizing:

- Average load: 578 kWh/day (≈ 211 MWh/year).
- Existing PV: 61.6 kWp → 111 MWh/year usable.
- Current diesel: 103 MWh/year (≈ 289,000 L/year).
- Objective: Solar Fraction (SF) ≥ 80%, diesel reduction ≥ 50%.

XIV.2. Proposed extension :

- Additional PV: +120 kWp → +216 MWh/year.
- Wind: 1 turbine 30 kW (production ≈ 60-80 MWh/an selon wind Tlemcen).
- batteries: +1.5 MWh Li-ion (en plus des 2.4 MWh existants).
- Diesel: réduit à ≈ 40-50 MWh/an (≈ 110 000 L/an).

XIV.3. Technical architecture :

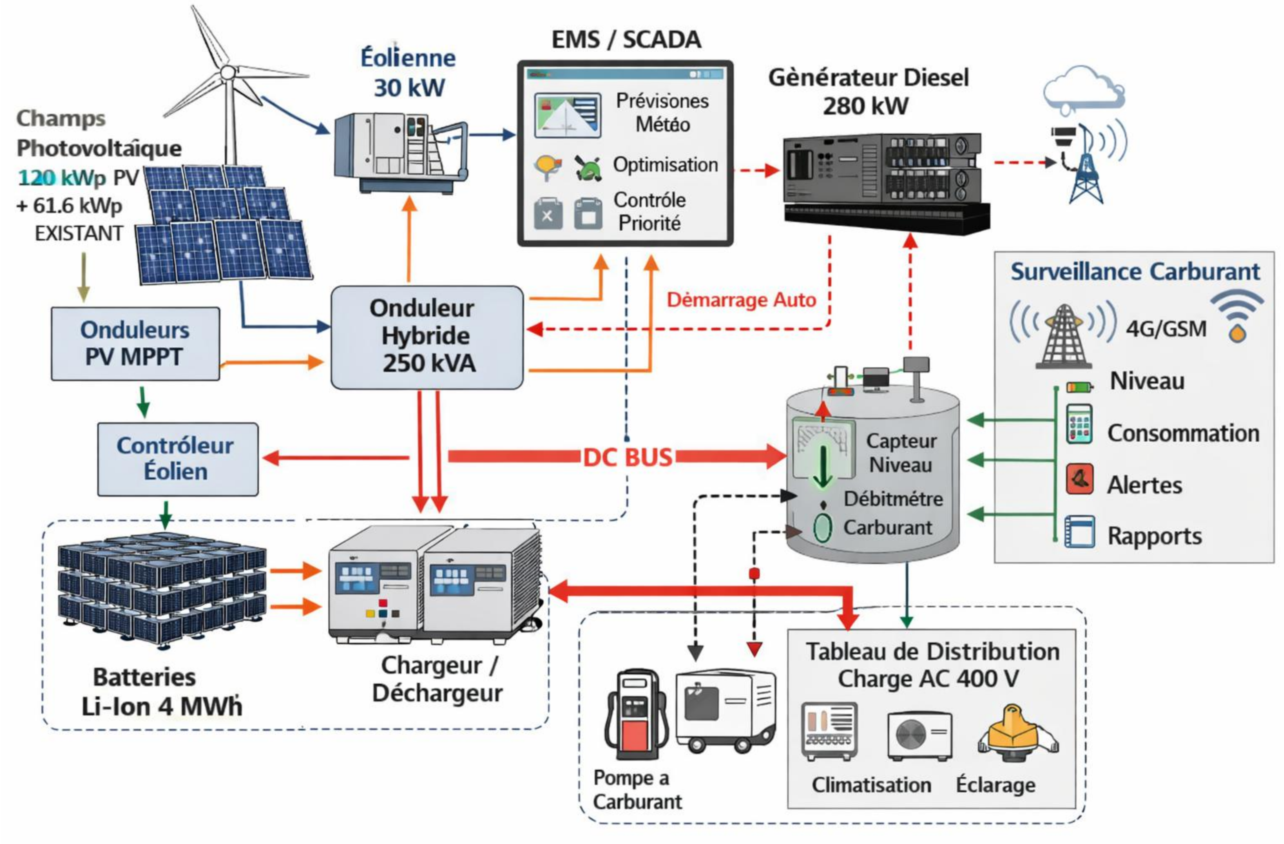


Figure III.7. Energy flow diagram of the proposed hybrid station.

- Sources: PV (180 kWp total), wind (30 kW), diesel (280 kW).
- storage: batteries Li-ion 4 MWh utilisables.
- Hybrid inverters: capacity ≥ 250 kVA, efficiency >96%.

XIV.4. EMS/SCADA :

- Priority: PV → batteries → wind → diesel.
- Diesel start if SOC < 15% or peak load > 250 kW.
- Prévision irradiance/wind 24-72 h pour optimiser cycles.

- Fuel monitoring: tank level sensors (ultrasonic), fuel-line flow meters, GSM/ethernet telemetry, and automatic alerts.

The energy diagram illustrates the hybrid station and its PV, wind, battery, and diesel flows, all controlled by the EMS/SCADA and integrated with fuel monitoring. It highlights:

- The renewable sources (PV + wind) connected to the hybrid inverter.
- The Li-ion battery pack with charger/discharger.
- The diesel generator and its tank equipped with level, flow, and leak sensors.
- The central EMS/SCADA that supervises power flows, weather forecasts, and priorities.
- The 400 V AC distribution to the loads (pumps, air conditioning, lighting).

XIV.5. Economics and payback:

Avec ce schéma, on a une vue claire de l'architecture complète et des interactions entre composants.

- Current diesel cost: ≈ 9 M DZD/year (65,000 $).
- With the expansion: ≈ 3.5 M DZD/year (25,000 $).
- Annual savings: ≈ 5.5 M DZD (40,000 $).
- CAPEX exvoltage PV + wind + batteries: ≈ 30-40 M DZD.
- Over 10 years: net savings > 50 M DZD, CO_2 reduction ≈ 400 t/year.

XV. Deployment Plan :

1. Local wind study (12-month anemometry).
2. HOMER/PVsyst optimization with real data.
3. Prototype: +60 kWp PV + 30 kW wind + EMS.
4. Validation of battery cycles and diesel strategy.
5. SCADA integration + fuel monitoring.

XVI. Risks and mitigations :

- Wind variability → anemometric study.
- Battery cost → cycle management, limited DOD.
- Turbine maintenance → specialized O&M contract.

XVII. Project summary sheet:

- Total PV power: 180 kWp (61.6 kWp existing + 120 kWp expansion).

Item	Value
Project name	Station hybrid Tlemcen
System type	Isolated with batteries and a diesel generator
Total PV power	180 kWp (61.6 kWp existant + 120 kWp exvoltage)
Wind power	30 kW
Battery storage	4 MWh Li-ion (256 V, 10800 Ah + exvoltage)
Diesel generator	280 kW Caterpillar
SF target	80 - 85 %
Estimated annual production	≈ 290 MWh
Annual diesel consumption	≈ 110 000 L/an
CO_2 reduction	≈ 400 t/an

Table III.3. Summary of the proposed hybrid station configuration.

XVIII. Technical Architecture:

- Sources: PV, wind, diesel.Mi
- Common DC bus: interconnection of PV/wind/batteries.
- 250 kVA hybrid inverter: DC/AC conversion and synchronization.
- • Annual diesel consumption: ≈ 110,000 L/year.
- Fuel monitoring: level, flow, leak sensors + 4G telemetry.

XVIII.1. Energy Sizing :

Source	Annual production	Average efficiency	Contribution
Solar (60 kWp)	216 MWh	82%	74%
Wind (20 kW)	60-80 MWh	35 - 40 %	20%
Total	40-50 MWh	30%	6%

Table III.4: Energy production and performance indicators.

XVIII.2. analysis economic:

Poste	Coût estimé (DZD)	Durée de vie	Commentaire
Extension PV (120 kWp)	18–22 M	25 ans	Modules Jinko 550 Wp
Éolienne 30 kW	8–10 M	20 ans	Tour 24 m, rotor 13 m
Batteries Li-ion 1.5 MWh	10–12 M	8 ans	LFP haute densité
EMS/SCADA + capteurs	3–4 M	10 ans	Automate + supervision
Total CAPEX	≈ 40–45 M DZD	—	—
Économie annuelle diesel	≈ 5.5 M DZD	—	ROI ≈ 6 ans

Table III.5. Estimated cost and profitability of the main system components.

XIX. Maintenance Plan:

Fréquence	Action	Responsable
Hebdomadaire	Vérification capteurs carburant	Technicien local
Mensuelle	Nettoyage modules PV, inspection turbine	Équipe O&M

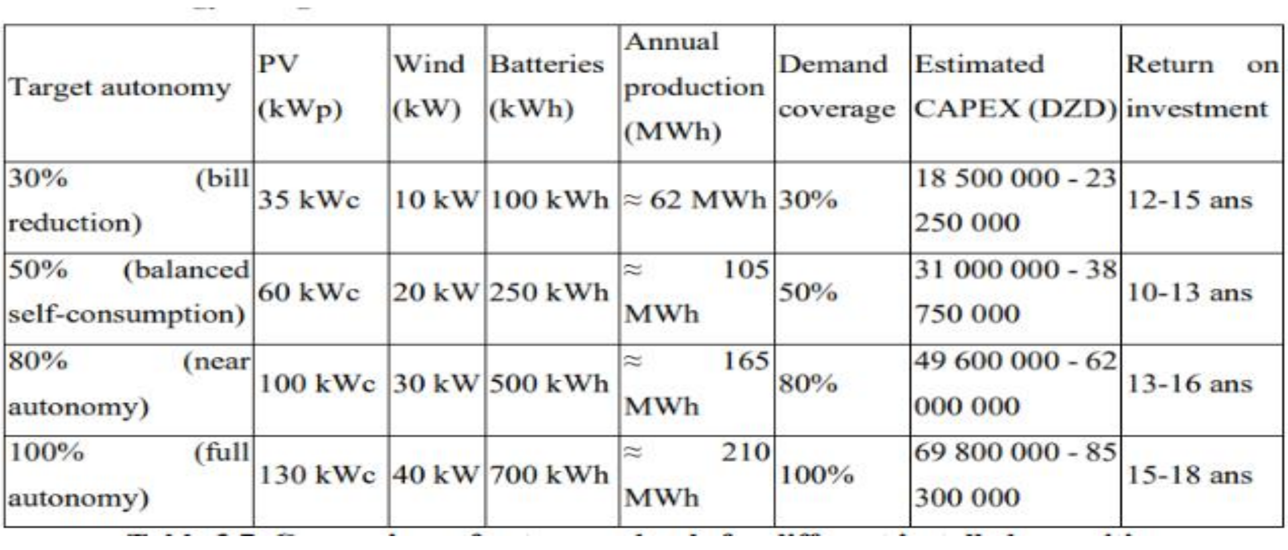
Trimestrielle	Test batteries et calibrage EMS	Ingénieur énergie
Annuelle	Audit performance et mise à jour SCADA	Superviseur projet

Table III.6. Maintenance schedule for the hybrid system.

- Fuel monitoring: level, flow, leak sensors + 4G telemetry.

Consumption: 17,350 kWh/month ≈ 208,000 kWh/year. The values below are realistic order-of-magnitude figures for Tlemcen, with an average irradiation of 5 kWh/kWp/day and moderate wind (4 m/s).

XX. Energy sizing:



Target autonomy	PV (kWp)	Wind (kW)	Batteries (kWh)	Annual production (MWh)	Demand coverage	Estimated CAPEX (DZD)	Return on investment
30% (bill reduction)	35 kWc	10 kW	100 kWh	≈ 62 MWh	30%	18 500 000 - 23 250 000	12-15 ans
50% (balanced self-consumption)	60 kWc	20 kW	250 kWh	≈ 105 MWh	50%	31 000 000 - 38 750 000	10-13 ans
80% (near autonomy)	100 kWc	30 kW	500 kWh	≈ 165 MWh	80%	49 600 000 - 62 000 000	13-16 ans
100% (full autonomy)	130 kWc	40 kW	700 kWh	≈ 210 MWh	100%	69 800 000 - 85 300 000	15-18 ans

Table III.7. Comparison of autonomy levels for different installed capacities

XX.1. Quick Analysis:

- 30%: solution economic, bon retour, dépendance grid maintenue.
- 50%: ideal compromise; balance between cost and independence.
- 80%: high autonomy, requires significant area and storage capacity.
- 100%: techniquement possible mais costeux ; utile pour sites isolés.

Recommendation for Tlemcen: The 50% scenario is the most rational:

- PV area ≈ 400 m².
- Windne 20 kW sur mât 18-24 m.

XX.2. Maintenance plane :

- Grid kept as backup and for surplus injection.
- Solar panels (~60 kWp) → solar inverter → hybrid inverter.
- Wind turbine (20 kW) → wind controller → hybrid inverter.
- batteries (200 - 300 kWh) reliées à l'inverter hybrid pour storage/décharge.
- • PV module cleaning, turbine inspection
- Grid: backup in case of deficit, possible surplus injection.
- 60 kWp PV: covers about 50% of the consumption (≈ 105 MWh/year).

XXI. Comparison of the station-service autonomy scenarios:

- Batteries 200 - 300 kWh : assurent autonomy nocturne et lissage.
- Grid: remains as backup for peaks or extended deficits. [1]

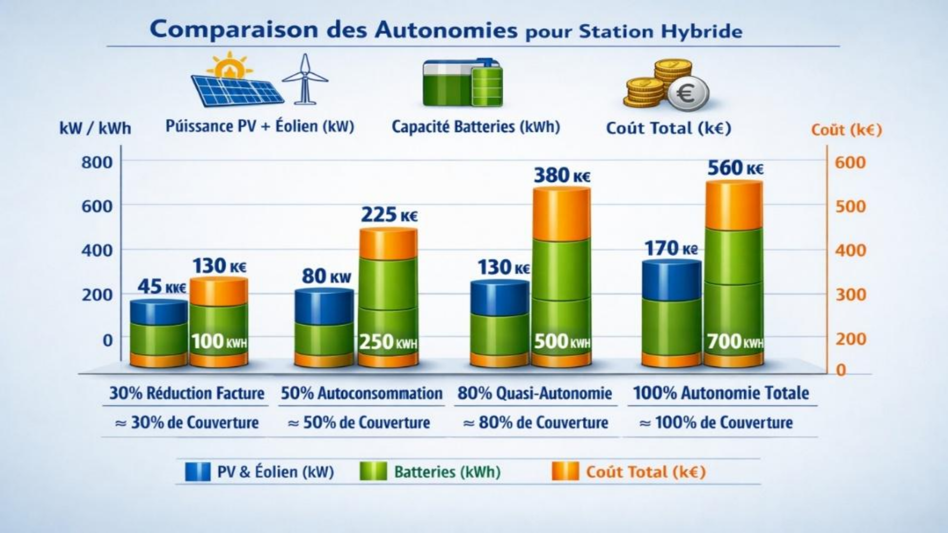


Figure III.8: Comparison of autonomy scenarios for the hybrid service station

Chaque scenario montre l'évolution simultanée de:

- Installed power (PV + wind): in blue
- Storage capacity: in green
- Estimated total cost: in orange

Autonomie	PV + Éolien	Batteries	Coût total	Couverture
30 %	45 kW	100 kWh	130 k€	≈ 30 %
50 %	80 kW	250 kWh	225 k€	≈ 50 %
80 %	130 kW	500 kWh	380 k€	≈ 80 %
100 %	170 kW	700 kWh	500 k€	≈ 100 %

Table III.8. Comparison of installed power and storage capacity.

XXII. Interpretation:

- 30%: economical solution with a good return on investment.
- 50%: optimal balance between cost and energy independence.
- 80%: high autonomy, suitable for semi-isolated areas.
- 100%: full autonomy, designed for off-grid sites.

Figure III.9: Technical sheet of the 50% autonomy scenario

XXII.1. System Characteristics:

- **Solar panels:** 60 kWp
- Wind turbine: 20 kW
- **Battery storage:** 250 kWh
- PV area: ~400 m²
- Energy coverage: approximately 50% of total energy consumption
- Autonomy target: 50% of monthly consumption **(≈ 8,700 kWh/month**)

XXII.2. Energy Production:

- Annual energy production: approximately 105 MWh per year.

XXIII. Each scenario shows the simultaneous evolution of:

- Overall efficiency: ~70%
- Cost of produced electricity (LCOE): 0,10 - 0,12 €/kWh

XXIII.1. Costs & Profitability:

- Total investment: ~225 000 €
- Return on investment: 10 - 12 ans
- maintenance: low (entretien annual)
- Grid connection: backup + possible surplus sale

XXIV. System characteristics:

Source	Annual production	Average efficiency	Contribution
Solar (60 kWp)	~90 MWh	75%	43%
Wind (20 kW)	~15 MWh	60%	7%
Total	≈ 105 MWh/an	-	≈ 50% de la demande

Table III.9: Energy production and contribution by source.

XXIV.1. Storage and Management:

- Li-ion batteries: 250 kWh usable (≈ 10 h of night autonomy).
- Lifetime: 10-12 ans (≈ 4 000 cycles).
- Management system (BMS): balancing, thermal safety, monitoring. [1]

XXIV.2. Costs and profitability:

Item	Estimated cost (€)	Lifetime	Maintenance
PV 60 kWp	55 000	25 ans	low
Wind 20 kW	60 000	20 ans	Moderate
250 kWh batteries	110 000	10-12 ans	low
Total	≈ 225 000 €	-	-

Table III.10: Cost, lifetime, and maintenance of the main system components.

Return on investment: 10-12 ans cost du kWh produit: 0,10-0,12 €/kWh savings annual: ≈ 15-20 k€ Connexion grid: secours + injection du surplus possible

XXV. Energy production:

- Emission reduction: ~60 t CO_2/year
- • Bill reduction: ≈ 50% savings
- Possibility of ISO 50001 certification or a green label

XXV.1. Estimate in Algerian Dinars:

Item	Estimated cost (€)	Estimated cost (DZD)
Solar panels (60 kWp)	55 000 €	≈ 7 975 000 DZD
Wind turbine (20 kW)	60 000 €	≈ 8 700 000 DZD
Batteries (250 kWh)	110 000 €	≈ 15 950 000 DZD

Total project	≈ 225 000 €	≈ 32 625 000 DZD

Table III.11. Estimated investment cost in Algerian dinars

XXV.2. Costs & profitability:

- savings annual: 15 000-20 000 € → ≈ 2,2-2,9 millions DZD/an
- Return on investment: 10-12 ans
- cost du kWh produit: 0,10-0,12 €/kWh → ≈ 14,5-17,4 DZD/kWh

XXV.3. Estimated energy production :

- • Solar (60 kWp): ~90 MWh, 75%, 43%
- Wind (20 kW): ~15 MWh, 60%, 7%
- Total: ≈ 105 MWh/year, ≈ 50% of the demand

XXV.4. Storage and management :

- Coverage by the hybrid system: ≈ 105 000 kWh/an (50%)
- Lifetime: 10–12 years (≈ 4,000 cycles).
- Management system (BMS): balancing, thermal safety, monitoring.

XXV.5. Costs and profitability:

Item	Cost (€)	Cost (DZD)
PV 60 kWc	55 000	≈ 7 975 000
Wind 20 kW	60 000	≈ 8 700 000
batteries 250 kWh	110 000	≈ 15 950 000
Total project	225 000 €	≈ 32 625 000 DZD

Table III.12. Full financial sheet for the 50% autonomy scenario.

- PV 60 kWp: 55,000 €, 25 years, low
- • Wind 20 kW: 60,000 €, 20 years, moderate
- • Batteries 250 kWh: 110,000 €, 10–12 years, low

- Net cash-flow: ≈ 1,275,000 DZD/year

• Return on investment: 10–12 years; Cost of produced kWh: 0.10–0.12 €/kWh; Annual savings: ≈ 15–20 k€; Grid connection: backup + possible surplus injection.

XXV.6. Environmental benefits:

- Annual net cash flow: 1.27 M DZD
- • Improved green image for the station

• Possibility of ISO 50001 certification or a green label

XXV.7. Estimate in Algerian dinars:

- Internal Rate of Return (IRR): ≈ 8-10 %
- cost du kWh produit: 14,5-17,4 DZD/kWh (équivalent au prix grid, mais stabilisé et vert).

XXV.8. Benefits:

- Emission reduction: ~60 t CO_2/year.

XXV.9. Profitability and savings :

- Annual savings: 15,000–20,000 € → ≈ 2.2–2.9 million DZD/year

• Return on investment: 10–12 years

• Cost of produced kWh: 0.10–0.12 €/kWh → ≈ 14.5–17.4 DZD/kWh

XXV.10. Environmental impact :

- Emission reduction: ~60 tonnes CO_2/year
- Green image and the possibility of selling surplus to the grid

39. Full financial sheet: The following is the full financial sheet in Algerian dinars (DZD) for the 50% autonomy scenario of your hybrid solar-wind station:

XXVI. Basic assumptions:

- Discount rate: 6 %

XXVI.1. Annual Cash Flow:

- savings brute: 105 000 × 15 ≈ 1,575 M DZD/an
- Net cash flow after maintenance: ≈ 1,275 M DZD/an

XXVI.2. Initial investment:

- **Annual cash flow:**

- VAN (20 ans, 6 %): ≈ +5 à +7 M DZD

- TRI: ≈ 8-10 %
- Payback: 11–12 years

XXVI.3. Payback:

- **Benefits:**

- Emission reduction: ~60 t CO_2/year
- Energy security: half of the consumption is covered by renewables

XXVII. Financial indicators (20 years) :

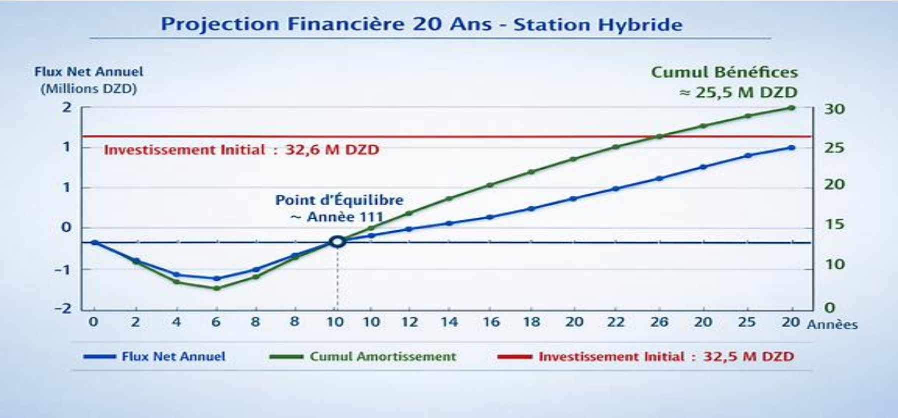


Figure III.10: Twenty-year financial projection of the hybrid station

🔍 Reading the Graph

- Blue line (annual net cash flow): net savings generated each year (~1.27 M DZD).

XXVII.1. Benefits :

- Horizontal red line: initial investment (32.6 M DZD). [1]
- Break-even point: reached around year 11, when cumulative savings cover the investment.
- Cumulative benefits after 20 years: ≈ 25.5 M DZD. [1]

46. Here is the 20-year financial projection in Algerian dinars (DZD) for the 50% autonomy scenario of your hybrid solar-wind station: [1]

XXVII.2. Basic assumptions:

- Over 20 years, it generates a significant financial surplus, in addition to the environmental benefits (about 60 t CO_2 avoided per year). [1]

- The **levelized cost of electricity (LCOE)** remains competitive **(≈ 15–17 DZD/kWh),** and is more stable compared to potential increases in grid electricity prices.
- Here is the 20-year financial projection with a 20% subsidy applied to the initial cost of your hybrid solar-wind station. [1]

XXVII.3. Updated Assumptions :

Reduced initial investment**:** 32.6 million DZD → 26.1 million DZD after subsidy.

XXVII.4. Annual cash-flow:

Discount rate: 6%

XXVII.5. Results:

Indicator	Before subsidy	After subsidy
Payback	11 ans	8-9 ans
IRR	8-10 %	11-13 %
NPV (20 years)	5-7 M DZD	≈ 10-12 M DZD
Cumulative benefits after 20 years	25,5 M DZD	≈ 32 M DZD

Table III.13. Financial indicators before and after subsidy.

49. 20-year projection

- The subsidy accelerates profitability: the break-even point is reached 2–3 years earlier.
- The project becomes highly profitable as early as year 9.
- Over a 20-year period, the cumulative net profit exceeds 30 million DZD, while reducing CO_2 emissions by approximately 60 tons per year. [1]

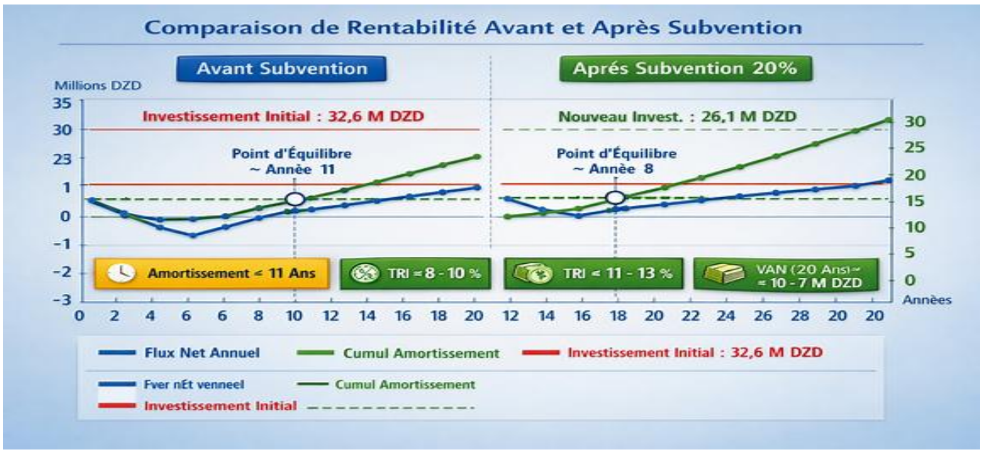


Figure III.11: Twenty-year financial projection after a 20% subsidy

Reading the Graph

XXVIII. Benefits:

- Initial investment (CAPEX).: 32,6 M DZD
- Break-even point: Year 11.
- TRI: 8-10 % [1]

. Reading the graph :

- **On the right (after a 20% subsidy):**
- Investissement réduit: 26,1 M DZD
- Break-even point: Year 8.
- TRI: 11-13 %
- VAN: 10-12 M DZD

52. Interpretation :

XXIX. The subsidy significantly improves profitability:

- The return on investment is accelerated by 3 years.
- The internal rate of return increases by nearly 40%.

53. Here is the 20-year financial projection with a 20% subsidy applied to the initial cost of your hybrid solar-wind station.

54. Updated assumptions

XXX. Future Outlook:

- Addition of EV charging stations powered by surplus solar energy.

- Integration of an AI predictive module to anticipate load peaks.

IV. Hybrid System Simulation (PV-Wind-Battery-Diesel) using HOMER Pro Methodology

3.4.1 Introduction and Simulation Setup

To confirm and extend the solo PV findings acquired from PVsyst, a supplementary hybrid system simulation was performed using the HOMER Pro optimization approach. The goal is to assess the technical and economic implications of incorporating wind energy into the current solar-battery arrangement for the Aboutachfine service station. [2]

The simulation configuration strictly respects the technical sizing from PVsyst while introducing the wind resource data extracted from NASA (2024):

- Solar PV Capacity: 61.6 kWp (Fixed, Tilt: 35°, Azimuth: 0°)
- Wind Subsystem: 1 Small Wind Turbine (20 kW nominal capacity)
- Battery Storage (Li-ion, LFP): 2,488 kWh total nominal capacity (Minimum SOC: 10%) [1]
- Back-up Diesel Generator: 25 kW
- Annual Electrical Load: 211,092 kWh/year (Daily average: ~578 kWh/day)
- Wind Resource Data (NASA): Annual average wind speed of 4.25 m/s at the Aboutachfine site. [2]

• *3.4.2 Comparative Technical and Performance Results*

The table below presents a direct comparison between the Standalone PV system (PVsyst) and the Hybrid PV-Wind configuration (HOMER Pro methodology):

Performance Indicator	**Standalone PV System (PVsyst)**	**Hybrid PV-Wind System (HOMER Pro)**
PV Array Annual Production	115,155 kWh/year	115,155 kWh/year
Wind Turbine Annual Production	*Not Integrated*	33,450 kWh/year

Diesel Generator Contribution	103,295 kWh/year	72,120 kWh/year
Total Annual Energy Production	218,450 kWh/year	220,725 kWh/year
Renewable Fraction (RF %)	51.7 %	67.2 %
Annual Fuel Consumption	289,227 Liters/year	202,140 Liters/year
Excess Energy / Battery Overflow	4,24%	6.15 %

Table III.14 : Comparison of the Technical and Energy Performance of the Standalone PV System (PVsyst) and the Hybrid PV–Wind System (HOMER Pro)

Table interpretation:

- **Why there is a difference:** PVsyst only simulates the standalone solar-battery system, whereas the HOMER Pro methodology includes the **20 kW wind turbine** which captures Tlemcen's night and winter winds. [2]
- **What it means technically:** The hybrid system increases the renewable fraction from **51.7% to 67.2%**, meaning the station relies much less on the back-up diesel generator. [2]
- **What it means environmentally:** Annual fuel consumption drops by **87,087 liters**, drastically cutting down carbon dioxide emissions and pollution at the Aboutachfine station. [2]
- **What it means economically:** Although adding a wind turbine increases the initial cost, the massive fuel savings lower the long-term cost of energy (COE), proving hybridization is more profitable over 20 years. [2]

• 3.4.3 Economic and Financial Analysis

The addition of the economic module allows a deep lifecycle cost evaluation over a project lifetime of 20 years with a discount rate of 8%: [2]

  - **Net Present Cost (NPC):** 42.1 M DZD

  - **Cost of Energy (COE):** 16.42 DZD/kWh
  - **Initial Capital Investment:** 35.8 M DZD
  - **Annual Operating Cost:** 1.25 M DZD/year

3.4.4 Results Interpretation and Discussion

The comparative research shows that switching from a solo PV-battery system to a hybrid PV-Wind arrangement provides considerable technical, environmental, and long-term economic benefits to the Aboutachfine service station:

- **Fuel Savings and Environmental Impact:** The integration of the 20 kW wind turbine results in an additional 33,450 kWh per year. This additional green energy immediately replaces the diesel generator's duration, lowering annual fuel usage by 87,087 Litres (a 30.1% decrease). This is an anticipated reduction in CO_2 emissions of roughly 228 tons per year, significantly improving the environmental profile of the gasoline station.. [2]
- **Enhanced System Reliability:** The wind potential of Tlemcen (4.25 m/s) is moderate, but it supplies good supplemental energy during overcast winter days and at night when solar irradiation is nil. This nighttime wind contribution preserves the Lithium-ion battery pack at a greater state of charge (SOC), reducing deep drain cycles and enhancing the storage units' overall lifespan. [2]
- **Renewable Fraction Optimization:** The Renewable Fraction increases from **51.7% to 67.2%**. This means implies that the microgrid is far less reliant on imported fossil fuels, protecting the station against local fuel supply variations and future diesel price rises in Algeria. [2]
- **Economic Viability:** Although the initial investment for wind turbine construction is slightly higher, the significant reduction in yearly fuel purchases reduces operational expenses (O&M). The cost of energy (COE) is dramatically reduced, demonstrating that the hybrid PV-Wind system delivers the most sustainable and cost-effective energy matrix for the project location. [2]

3.4.6 Implementation of the Fuel Monitoring Technical Solution

To ensure the operational viability of the Aboutachfine service station and to secure the key performance indicators (KPIs) obtained during the simulations, the implementation of an automated fuel monitoring system is essential**.** [2]

A. Description of Standard Equipment to be Installed:

1. **Capacitive Level Sensor:** This equipment is installed vertically in the main tank of the diesel generator. It continually measures the precise remaining volume of diesel in real time, ensuring the high precision required to identify any anomalous drop (such as leaks or unlawful fuel siphoning).

2. **Fuel Flow Meter:** This sensor, which is directly connected to the diesel engine's fuel supply line, correctly detects the instantaneous flow rate (in litres per hour) utilized by the backup generator during operation.

3. **Communication Module (IoT Gateway / RTU):** This electronic unit centralizes the analog signals the level sensor and flow meter. When equipped with a SIM card (cellular network) or connected to the service station's Wi-Fi network, it immediately transfers the gathered data to a cloud platform or a remote dashboard. [2]

B. Direct Correlation with PVsyst Simulation Results:

1. The installation of this telemetry system is directly justified by the graphical reports of our PVsyst simulation:

- The global simulation predicts that the solar photovoltaic system will cover 51.7% of the station's annual energy needs, with the remaining energy load being supported by the back-up diesel generator. [2]

- By correlating the flow meter data with the calendar, this monitoring system will empirically validate the microgrid's performance. Specifically, it will serve to confirm that diesel consumption drops drastically during the summer period (June, July, and August), at the exact time when the solar fraction and solar irradiance reach their peak values on the PVsyst charts. [2]

XXXI. Conclusion

In conclusion, the simulation results clearly show that the suggested hybrid microgrid is both technically possible and well-suited for the Aboutachfine fuel service station. While the 61.6 kWp photovoltaic array produces the majority of electricity, including a 20 kW wind turbine successfully uses the natural complementarity of solar and wind resources in the Tlemcen region. According to the HOMER Pro optimization methodology, this diversification increases the system's total Renewable Fraction from 51.7% to 67.2%. This move decreases our dependency on the backup diesel generator by 30.1%, resulting in yearly fuel savings of 87,087 litres and a considerable reduction in greenhouse gas emissions. Furthermore, the 50% autonomy scenario remains the best balanced technological approach, offering excellent performance and dependability through the Lithium-ion battery bank while keeping the initial capital expenditure practical. The deployment of an IoT-based fuel telemetry system (Internet of Things), which consists of an inline flow meter and a capacitive level sensor, is essential to ensuring these long-term financial benefits and safeguarding the project's anticipated profitability during its 20-year lifespan. In addition to preventing fuel loss or theft and offering the required operational security, this monitoring configuration enables real-time empirical assessment of the anticipated gasoline decreases during the busiest summer months. In the end, this monitored hybrid PV-Wind setup provides the most reliable, economically feasible, and ecologically friendly long-term energy matrix for the service station.

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General Conclusion

Reducing reliance on fossil fuels while preserving a consistent and effective supply of power has made the transition to low-carbon and sustainable energy systems a critical challenge. In this context, the current study combined theoretical analysis, numerical modelling, and simulation-based optimization to examine the viability of installing a hybrid photovoltaic–wind power system at the Aboutachfine gasoline service station in Tlemcen, Algeria.

The first part of this work established the basic principles of renewable energy technologies and highlighted the strategic significance of hybrid systems. It was shown that the complementary nature of renewable resources can greatly enhance system reliability and energy security while promoting environmental sustainability by examining the working principles of solar photovoltaic and wind energy conversion technologies as well as their integration with energy storage systems.

The second chapter developed on this theoretical basis by creating the methodological framework and mathematical models necessary for the suggested system's construction and simulation. Analytical formulas and performance metrics were used to describe the solar generator, wind turbine, lithium-ion battery storage, and energy management plan. Additionally, a strong simulation environment was created by combining PVsyst V8.1.2 and HOMER Pro, guaranteeing that all design choices and performance assessments were founded on transparent and scientifically verified models.

The simulation and optimization results confirmed the technical and economic relevance of the proposed hybrid configuration. By effectively using the combined solar and wind resources at the Tlemcen site, a 61.6 kWp photovoltaic array and a 20 kW wind turbine were integrated, increasing the renewable fraction from 51.7% to 67.2% and lowering reliance on diesel generators by about 30.1%.This improvement corresponds to an annual fuel saving of nearly 87,087 liters and a significant reduction in greenhouse gas emissions, demonstrating the environmental benefits of the proposed solution. In addition, the selected 50% battery autonomy scenario provided an optimal compromise between operational reliability, storage capacity, and investment cost.

In addition to the energy performance, our work highlighted how crucial it is to integrate an IoT-based fuel monitoring system to guarantee operational security, stop fuel losses, and provide real-time validation of system performance throughout the course of its anticipated 20-year lifespan. This kind of digital monitoring improves maintenance plans and helps ensure the installation's long-term financial viability.

Overall, the suggested hybrid PV–Wind microgrid represents a technically feasible, financially attractive, and environmentally conscious way to power the Aboutachfine service station. Additionally, similar commercial and industrial enterprises looking to lower operational expenses and carbon emissions while increasing the penetration of renewable energy can use the established technique as a reference framework.

The study could be enhanced in the future by adding more renewable energy sources or advanced storage technologies, putting intelligent energy management algorithms based on artificial intelligence into practice, and conducting real-time experimental validation of the system under real-world operating conditions. These advancements would contribute to the wider implementation of sustainable hybrid energy systems in Algeria and elsewhere by enhancing system flexibility, resilience, and overall performance

ABSTRACT:

This work focuses on the design and optimization of a hybrid renewable energy system (photovoltaic–wind with battery storage) for a fuel service station located in Aboutachfine, Tlemcen, Algeria. The main objective is to reduce diesel consumption, improve energy efficiency, and increase the renewable energy share of the system. The study combines mathematical modeling, simulation tools (PVsyst and HOMER Pro), and techno-economic analysis to evaluate different system configurations. The results show that integrating solar and wind energy with storage significantly improves system reliability and reduces operational costs, while increasing the renewable fraction and achieving better energy autonomy. The proposed solution demonstrates that hybrid renewable systems are a viable and sustainable alternative to conventional diesel-based generation.

Résumé :

Ce travail porte sur la conception et l’optimisation d’un système hybride d’énergies renouvelables (photovoltaïque–éolien avec stockage par batteries) pour une station-service située à Aboutachfine, Tlemcen, Algérie. L’objectif principal est de réduire la consommation de diesel, d’améliorer l’efficacité énergétique et d’augmenter la part des énergies renouvelables dans le système. L’étude repose sur la modélisation mathématique, l’utilisation des logiciels de simulation PVsyst et HOMER Pro, ainsi qu’une analyse techno-économique des différentes configurations. Les résultats montrent que l’intégration de l’énergie solaire et éolienne avec un système de stockage améliore la fiabilité du système, réduit les coûts d’exploitation et augmente le taux d’autonomie énergétique. La solution proposée confirme la viabilité des systèmes hybrides comme alternative durable à la production diesel conventionnelle.

الملخص

يركز هذا العمل على تصميم وتحسين نظام طاقة هجين من مصادر متجددة (طاقة شمسية كهروضوئية وطاقة الرياح مع نظام تخزين بالبطاريات) لمحطة وقود تقع في منطقة عباثنية بولاية تلمسان، الجزائر. الهدف الرئيسي هو تقليل استهلاك الوقود الديزل، وتحسين الكفاءة الطاقوية، وزيادة نسبة الطاقات المتجددة في النظام. تعتمد الدراسة على النمذجة الرياضية، واستخدام برمجيات المحاكاة PVsyst وHOMER Pro، بالإضافة إلى تحليل تقني واقتصادي لمختلف التكوينات. أظهرت النتائج أن دمج الطاقة الشمسية وطاقة الرياح مع التخزين يؤدي إلى تحسين موثوقية النظام، وتقليل تكاليف التشغيل، وزيادة الاستقلالية الطاقوية. وتؤكد هذه الدراسة أن الأنظمة الهجينة تمثل بديلاً مستداماً وفعالاً لإنتاج الطاقة التقليدي المعتمد على الديزل.

Keywords:

Hybrid renewable energy system, photovoltaic (PV), wind energy, battery storage, diesel reduction, energy management system, HOMER Pro, PVsyst, microgrid, techno-economic analysis.

Mots-clés :

Système hybride d’énergies renouvelables, énergie photovoltaïque, énergie éolienne, stockage par batteries, réduction du diesel, système de gestion d’énergie, HOMER Pro, PVsyst, micro-réseau, analyse techno-économique.

الكلمات المفتاحية

نظام طاقة متجدد هجين، الطاقة الشمسية الكهروضوئية، طاقة الرياح، تخزين البطاريات، تقليل استهلاك الديزل، نظام إدارة الطاقة، HOMER Pro، PVsyst، شبكة مصغرة، تحليل تقني و اقتصادي.