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Presented by:

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Title

Assessment of Efficiency and Operational Performance in Large-Scale Grid-Connected PV Installations

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إهداء

ولأن أحلامي لن تفنى، ولن أضيّع الطريق، ولن ينال اليأس منّي ولن ترعبني رهبة الفشل، ما خلقت لأهزم وما خلق الوصول إلّا لي. قويٌّ التوكل والدُّعاء لا يهزم ولن يخذل وما كان صبري عند الله منسيًّا واليوم ها أنا أرى دعواتي ودعوات أمي حقًّا، فالحمد لله دائما وأبدا.

أهدي هذا العمل إلى روحي وحبيبة الفؤاد إلى قبطان سفينتي وزهرة حياتي إلى **أمي**، هذا العمل لن يضاهي دعواتك في جوف الليل ودعمك في لحظات اليأس، من دونك لم أكن لأصل يومًا علمتني كيف أخطو أوّل خطواتي، جعلت مني امرأة الأزمات وسيدة اللحظات.

ولن أنسى **أبي** سندي الذي لا يميل من كنت استمد الثَّبات من يده وفي عينيه أرى نور أملي، البارحة مسكتَ يدي لأول فصل في دراستي واليوم أكمله معك.

الى مشرفي وعرّابي في الجامعة **البروفيسور هاني بن قسمية**، لطالما كانت الجامعة مرَّة وسكَّرها أنت، كنت كالمطر لأرض قاحلة، دعمك لا ينسى علَّمتني أن الانسان مُطالب بالسَّعي لا بالنَّتيجة واليوم أهديك النَّتيجة وكلي يقين أنَّك سبب من أسبابها ضحكتك ستبقى دوما في الذَّاكرة وإن خانت الذَّاكرة فستبقى دوما في القلب.

إلى إخوتي **أمين**، **عماد** و**شكيب** فرساني الثلاثة وحصني المنيع، كنتم سندي وكبريائي وستظلون كذلك.

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I send you my warmest regards,

ملخص:

يحلل هذا العمل أداء محطة طاقة كهروضوئية (PV) بقدرة إنتاجية تبلغ 20 ميغاواط(MW) ، تقع في منطقة عين الملح بالجزائر. يستند التقييم الحالي إلى بيانات تجريبية تم جمعها بين يناير وديسمبر 2019. تتكون المحطة من 40 حقلًا فرعيًا، كل منها مزود بمحول 500 كيلوواط و1936 وحدة كهروضوئية بقدرة 250 واط لكل منها. تم تحليل مجموعة من معايير الأداء، بما في ذلك العائد المرجعي، والعائد النهائي، وكفاءة الوحدة والنظام، ونسبة الأداء(P_R) ، ونسبة الأداء المعدلة، ومؤشرات أخرى متعلقة بالخسارة (الضياعات).

في هذه الدراسة، يتم تحليل أداء المحطةباستخدام طريقة جديدة لبيانات الإشعاع المائل المصحح ($G_{m,corr}$). يعمل الإشعاع المعدل على تحسين دقة مقاييس الأداء الرئيسية، بما في ذلك العائدات والكفاءة والخسائر، مما يوفر صورة أوضح عن كفاءة المحطة في مناخ الهضبة العالية.

الكلمات المفتاحية :طريقة الإشعاع المائل المصحح؛ تقييمات الأداء؛ نسبة الأداء؛ الكفاءة؛ النظام الكهروضوئي.

Abstract

This work analyses the performance of a photovoltaic (PV) power plant with an output capacity of 20 megawatts (MW), which is located in the region of Ain El-Melh, Algeria. The present assessment is founded on experimental data collated between January and December 2019. The plant consists of 40 sub-fields, each equipped with a 500 kW inverter and 1936 PV modules of 250 Wp each. A range of performance parameters are analyzed, including, reference yield, final yield, module and system efficiency, performance ratio (P_R), corrected PR, and other loss-related indicators.

In this study analyze the performance of this plant in 2019 using new method of corrected tilt radiation data ($G_{m,corr}$). The corrected tilt radiation improves the accuracy of key performance metrics, including yields, efficiencies, and losses, offering a clearer picture of the plant's efficiency in a high plateau climate.

Keyword: Method ofCorrected tilt radiation; Performance assessments; Performance ratio; Efficiencies ; PV system.

"List of Acronyms and Symbols"

List of Acronyms and Symbols

Acronyms

PV	solar photovoltaic
IEC	International Electrotechnical Commission
PVPA	Photovoltaic performance analyzer
IEA	International Energy Agency
STC	normal sunlight conditions
SKTM	Shariket Kahraba wa Takat Moutadjadida
SPE	Electricity Production Company
MPPT	Maximum Power Point Tracking
AC	Alternating current
DC	Direct current
GCPV	Grid-connected photovoltaic systems
AI	Artificial Intelligence
IEA	International Energy Agency
ANN	Artificial Neural Networks
SVM	Support Vector Machines
CNNs	Convolutional neural networks
RNNs	Recurrent neural networks
LSTM	Long-term memory units
GRU	gate recurrent units
IRT	Infrared Thermography Analysis
SDO	Société de Distribution d'Électricité de l'Ouest
SDC	Société de Distribution d'Électricité de la Centre
LV	Low voltage
HV	High voltage
CO2	Carbon dioxide

Symbols

I_{pv}	Photovoltaic current
I_{ph}	Photo-generated Current

I_s	Reverse Saturation Current
R_s	Series resistor
R_{sh}	Shunt resistor
V_{pv}	Voltage delivered by the PV cell
η	Efficiency (%)
S	The cell area in m^2
E_{dc}	Energy generated by photovoltaic panel system (Wh)
P_{dc}	The power in direct current (W)
T_a	Ambient temperature
T_m	device temperature
v	wind speed
E_{ac}	Alternative energy (Wh)
P_{ac}	The AC alternative power (W)
Y_r	The reference efficiency
H_t	The total inclination irradiance (kWh/m^2)
G_0	the reference irradiance of the array (1 kW/m^2)
Y_a	Array yield
E_{dc}	DC Energy
I_{dc}	Direct Current
V_{dc}	Direct current voltage
P_{pv}	Photovoltaic power
Y_f	Final yield
E_{ac}	AC Energy
P_{ac}	AC output power
P_{dc}	DC output power
P_R	performance ratio
η_{sys}	The efficiency of the photovoltaic system (%)
A_t	The total surface modules
η_{inv}	Inverter Efficiency
η_A	Array Efficiency
CUF	Capacity Utilization Factor

L_S	System losses
L_c	Capture Losses
P_0	Rated power of the PV array (W).
V_{mppmin}	Minimum voltage at maximum power point
V_{mppmax}	Maximum voltage at minimum power point

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"General Introduction"

General Introduction

Algeria's energy landscape is deeply rooted in hydrocarbon production, with oil and gas fulfilling nearly all of the nation's energy needs. However, maintaining this reliance on fossil fuels presents long-term challenges for supply and demand. Therefore, the large-scale integration of alternative energy sources into the energy mix is crucial. This diversification strategy is essential not only for conserving fossil fuel reserves but also for promoting sustainable development and for ensuring a secure energy future.

This transition necessitates exploring and implementing renewable energy technologies, which are vital for reducing dependence on finite resources and mitigating the environmental impact of traditional energy production.[1,2]

The share of renewable energy in meeting global energy demand is projected to rise, with green energy production systems experiencing rapid growth, particularly in the electricity sector. Solar photovoltaic (PV) energy is a key driver of this expansion. In 2021, global photovoltaic capacity additions reached 183 GW, highlighting the increasing importance of PV technology in the global energy landscape.[3]

Algeria, with its geographical location and abundant solar resources, possesses significant potential for solar photovoltaic (PV) development. The country receives an average solar irradiation ranging from 5.5 to 6 $kWh/m^2/day$, making it an ideal location for harnessing solar energy.

Recognizing this potential, Algeria has embarked on an ambitious renewable energy program, targeting the installation of approximately 22,000 MW of renewable capacity by 2030. This commitment is reflected in the establishment of **Sonelgaz-Energies Renouvelables** (Sonelgaz-ER), a subsidiary of Sonelgaz, specifically tasked with developing and managing renewable energy projects across the country.[4]

Evaluating the performance of photovoltaic power generation systems requires standardized methodologies. The International Electrotechnical Commission (IEC) standard 61724 provides guidelines for performance monitoring, data exchange, and analysis [5]. This standard focuses on evaluating the overall system performance rather than individual components, enabling comparisons across different PV installations and climates.[5,6]

This thesis investigates the performance of the Ain El-Melh-M'sila photovoltaic power plant. The research is structured as follows:

Chapter I provides an overview of photovoltaic (PV) systems, including their primary components and the different types of PV systems available. It then outlines the key performance indicators used to evaluate PV system efficiency and associated losses. Additionally, the chapter identifies common faults that may occur in PV systems. Finally, it offers a comprehensive review of the latest strategies for fault detection and analysis in PV systems.

Chapter II offers a comprehensive overview of the Aïn El-Melh photovoltaic (PV) power plant, covering its geographical location, and key components. These include solar fields, junction boxes, inverters, the control room, the load communication cabinet, and environmental monitoring equipment.

Chapter III examines the performance of the Aïn El-Melh PV plant, addressing a critical issue: the inaccuracy of irradiance data resulting from pyranometer misalignment. This work proposes an innovative correction methodology that leverages synchronized DC current data. The objective of this methodology is to ensure a reliable performance analysis of 2019. This work reveals the plant's operational efficiency and energy yield under Algeria's unique conditions, and offers a scalable approach to enhance performance evaluations for large-scale PV plants worldwide.

The thesis concludes with a general conclusion summarizing the key findings and their implications.

<u>Chapter I</u>

″State of the art "PV systems"″

I.1. Introduction

In the last several years, the growing demand for renewable energy sources has led to huge advancements in solar photovoltaic (PV) technology which based on the directly conversation of sunlight into electricity using semiconductor materials making them a key player in the world's movement towards green solutions for energy. PV systems have widespread use in residential, commercial, and industrial installations. In chapter I, the objective is to present Overview of PV systems, their main components and types. It then identifies key performance indicators to evaluate its efficiency, their losses and classification of different faults may occur.

I.2. Overview of photovoltaic (PV) systems

Solar energy serves as a viable substitute for traditional fossil fuels. It is abundantly available and uniformly distributed across the Earth's surface, enabling the potential capture of up to 1000 W/m^2 in temperate regions, so the PV (Photovoltaic) system is a technology that converts sunlight directly into electricity using semiconductor materials. Their capacity to produce clean electricity plays a significant role in mitigating greenhouse gas emissions and fostering energy sustainability in both residential and commercial sectors.[7]

I.2.1. Components of a photovoltaic system

A photovoltaic (PV) system is designed to harness solar energy and convert it into electricity that can be used for various applications. The following is a detailed description of the key components and their function in achieving this conversion:

I.2.1.1. PV solar cell

Photovoltaic (PV) solar cells are devices that convert sunlight directly into electricity using semiconducting materials that exhibit the PV effect.

- **Understanding the photovoltaic (PV) effect**

The photovoltaic (PV) effect is the core mechanism that allows solar cells to convert sunlight into electricity. This process begins when photons from sunlight interact with a semiconductor material, typically silicon, within the solar cell. The semiconductor, exciting electrons and causing them to break free from their atomic bonds, creating electron-hole pairs, absorbs the energy from these photons. The internal electric field of the PV cell then directs the free electrons toward the conductive sides of the cell, while the holes move in the opposite direction. As the electrons flow through an external circuit connecting the positive and negative sides of the cell, they generate electrical current, which can be used to power devices. The output voltage of a typical solar cell is around 0.6 volts, with the current depending on factors like sunlight intensity and cell surface area. After flowing through the circuit, the electrons recombine with holes in the p-type region, completing the circuit. This cycle continues as long as the solar cell is exposed to sunlight, enabling a continuous generation of electrical energy.[8]

The figure I.1 shows a breakdown of the key components of this effect.

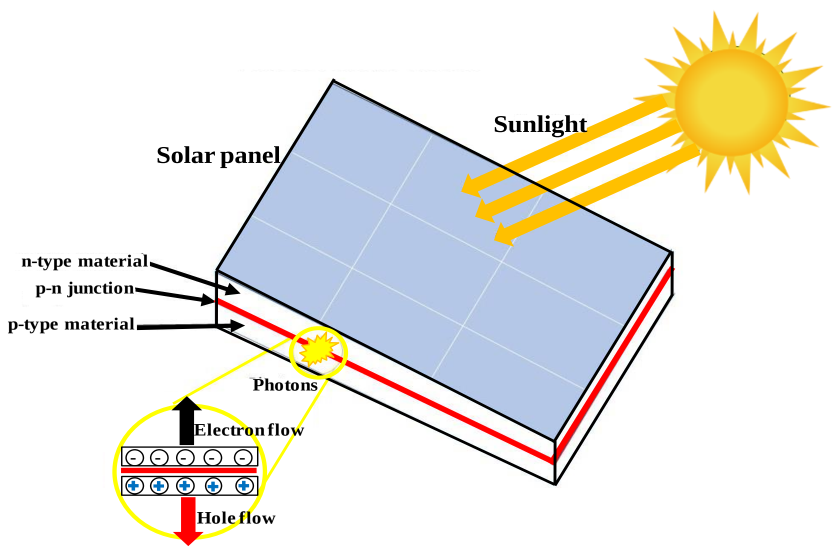

Figure I.1. Description the photovoltaic effect in solar cell.

Equivalent circuit of photovoltaic cell

The Figure I.2 provides a schematic representation of the equivalent circuit of a photovoltaic (PV) cell. The model of the circuit is constituted by the incorporation of a current source which is connected in parallel with a diode. In addition to this component, the model incorporates both a shunt resistor and a series resistor. The inclusion of these additional components is made in order to account for losses that are inherent to the cell, in addition to its electrical characteristics.[9]

The mathematic equation of photovoltaic cell given by:

$$I_{pv} = I_{ph} - I_0 (e^{\frac{V+IR_s}{nV}} - 1) - \frac{V - IR_s}{R_{sh}} \quad (I.1)$$

System producers usually specify the parameters I_{Ph}, I_0, R_s, R_{Sh} and n of the characteristic equation.

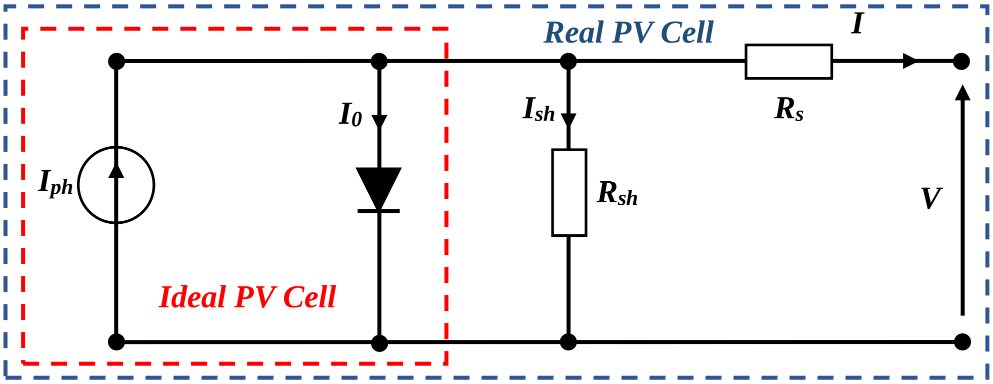

Figure I.2. The equivalent circuit model of PV cell.

I.2.1.2. PV module

The preponderance of silicon crystalline solar modules on the market, utilized in residential and commercial solar systems, underscores their predominance in the industry. The modules under consideration consist of a series of solar cells wired in a series configuration from positive to negative. They are mounted in an aluminum frame. Each solar cell possesses the capacity to generate 0.5 volts. A 36-cell module possesses a rating of 18 volts. Modules with greater dimensions are equipped with 60 or 72 cells within a single frame. The amperage of a photovoltaic module is contingent upon its cell size. An increase in cell dimensions corresponds to an increase in the module's amperage rating. In other words, the amperage is directly proportional to the cell size.[10]

I.2.1.3. PV panel

A PV panel, also known as a solar panel, is a larger unit composed of multiple interconnected photovoltaic (PV) modules. These modules, which are made up of individual solar cells, work together to capture sunlight and convert it into electricity through the photovoltaic effect.

I.2.1.4. PV array

A PV array is a configuration of multiple PV strings, where each string consists of a group of solar panels connected in series. When these strings are connected in parallel, they form a larger and more powerful system capable of generating higher electrical current while maintaining the same voltage as a single string.

I.2.1.5. PV generator

A PV generator refers to the entire photovoltaic power system that generates electricity.

A PV generator, also known as a photovoltaic generator, is a large-scale installation that comprises multiple PV arrays working together to generate significant amounts of electricity.[11]

This comprehensive system goes beyond just the solar panels and includes various essential components such as inverters, batteries, and tracking systems to optimize energy production and storage.

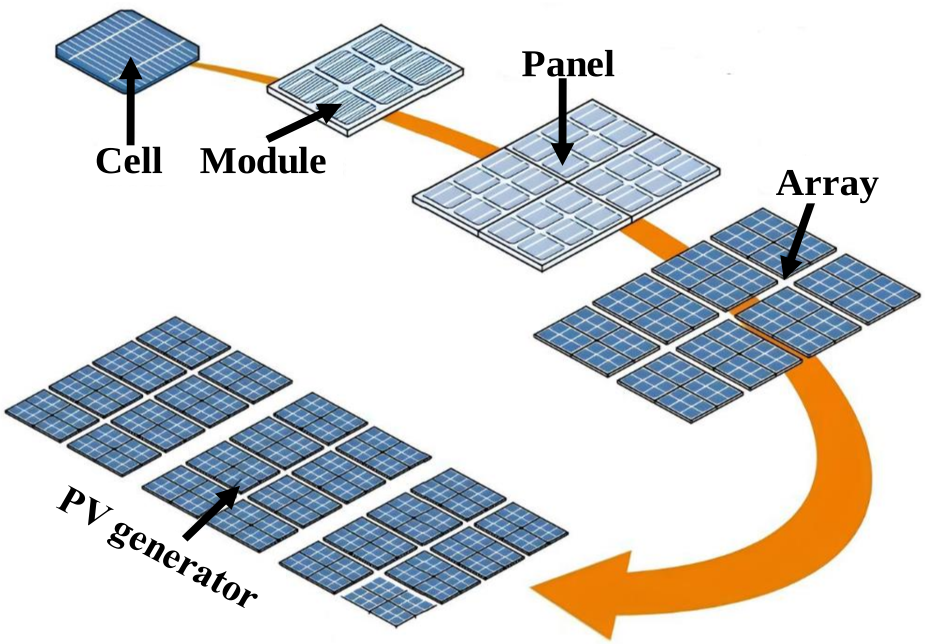

Figure I.3. Distinction about different photovoltaic architectures: from a cell to generators and parks.

I.3. Classification of PV systems

Photovoltaic (PV) systems can be broadly classified into three main categories based on their configuration and functionality: stand-alone systems, grid-connected systems and the hybrid systems. Stand-alone systems, also known as off-grid systems, operate independently of the electrical grid and rely on batteries for energy storage.[12]

These systems are commonly used in remote areas where grid access is unavailable or impractical, such as rural locations, cabins, or portable applications. The stored energy in the batteries ensures a continuous power supply, even during periods without sunlight, making stand-alone systems highly self-sufficient.

Then, the grid-connected systems, which are designed to interact with the electrical grid, allowing for the exchange of electricity between the PV system and the grid. These systems may or may not include batteries, depending on the specific design and energy requirements.

When batteries are incorporated, they provide backup power during grid outages or store excess energy for later use. Grid-connected systems are widely used in residential, commercial, and industrial settings, as they enable users to reduce electricity costs by feeding surplus energy back into the grid, often through net metering programs.

The Solar hybrid photovoltaic system is an advanced method of energy generation. These systems integrate photovoltaic technology with one or more renewable energy sources, such as wind, hydropower and a diesel generator, to create a more robust and dependable energy solution.

The flowchart in the figure I.4 illustrates the various configurations and components of PV systems, emphasizing the differences in their setup based on factors such as grid connectivity, energy storage needs, and the potential integration of additional power sources. This classification highlights the versatility of PV systems, allowing them to be tailored to diverse applications and energy demands.

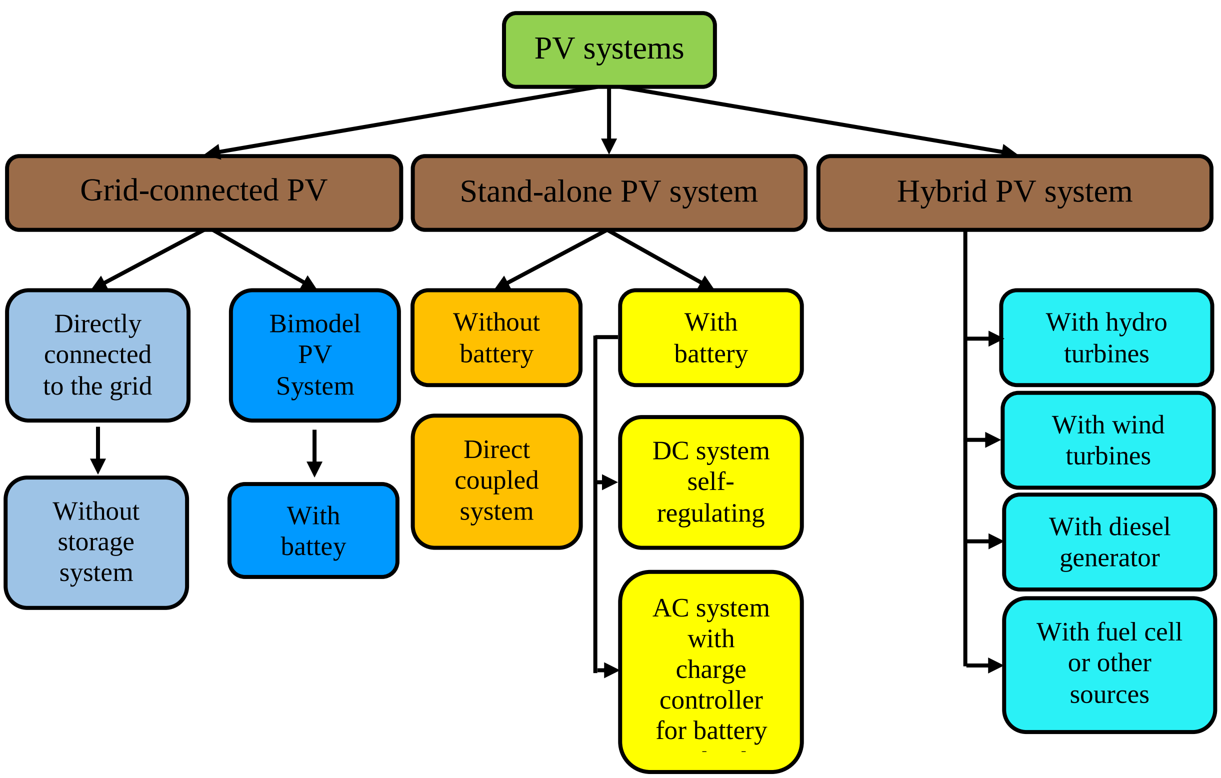

Figure I.4. Different types of Photovoltaic (PV) systems.

I.3.1. Stand-alone systems

Photovoltaic systems that are disconnected from the grid are designated as such due to their absence of contact with the utility distribution network and utilization of load storage systems.

These systems facilitate the storage of energy during periods of non-consumption, such as nocturnal hours or inclement weather conditions that are not conducive to energy generation.Year round conditions and weather changes have to be considered while designing this system.

In the figure I.3, we can see the inverter, which plays an essential role in transforming this DC electricity into alternating current (AC) for household appliances also we have the charge controller regulates battery use to prevent overcharging and extend battery life. This type of system is generally used in remote locations, such as farms, which do not have access to the electricity grid.

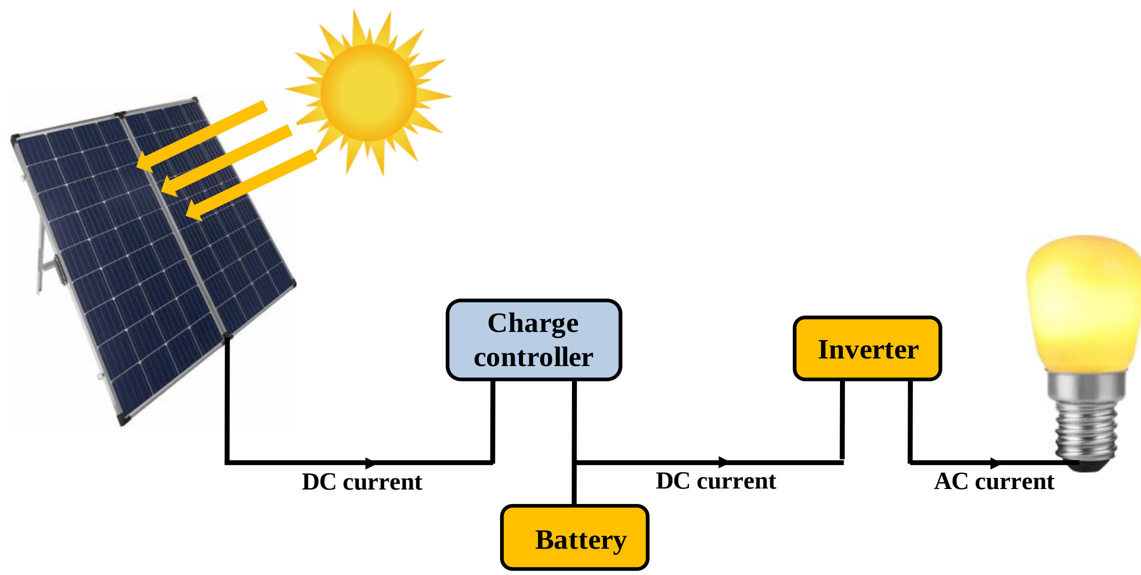

Figure I.5. Stand-alone photovoltaic system

I.3.2. Grid connected system

The grid connected system also named the grid tide PV system. Thus is engineered to work with local power grids, serves as an important solution to meet energy demands and integrate renewable sources in the existing infrastructure.

This photovoltaic system includes solar panels; inverters and equipment to provide connections to the grid (See the figure below).

- **PV Array:** The array is composed of multiple photovoltaic modules, which are made up of individual solar cells.

Depending on the configuration, the modules have the flexibility to be connected in series or in parallel, or both of them, to meet specific energy requirements. This arrangement optimizes energy output while maintaining system compatibility. [10,11,13]

- **Converters:** PV systems employ two primary converter types: DC/DC and DC/AC converters. These devices play a critical role in maximizing energy harvest by extracting the highest possible power from the PV array (via DC/DC converters) and converting direct current (DC) to alternating current (AC) for grid integration or AC appliance use (via DC/AC converters).
- **DC/DC Converters:** DC/DC converters, when integrated with Maximum Power Point Tracking (MPPT) algorithms, enable maximum power extraction by dynamically adjusting the operating point in real time to respond to changing environmental conditions. This process ensures that the PV generator operates at peak efficiency, even under varying conditions. This process stabilizes the PV generator at its peak efficiency under varying conditions and also helps extend the life of system components by preventing inappropriate overloading or under-loading.[7]
- **DC/AC Converters (Inverters):** In grid-connected photovoltaic (GCPV) systems, DC/AC inverters serve as vital components by transforming the DC output from PV arrays into grid-compatible AC power. This conversion enables seamless energy injection into the electrical grid and directly powers AC-based devices.[13]

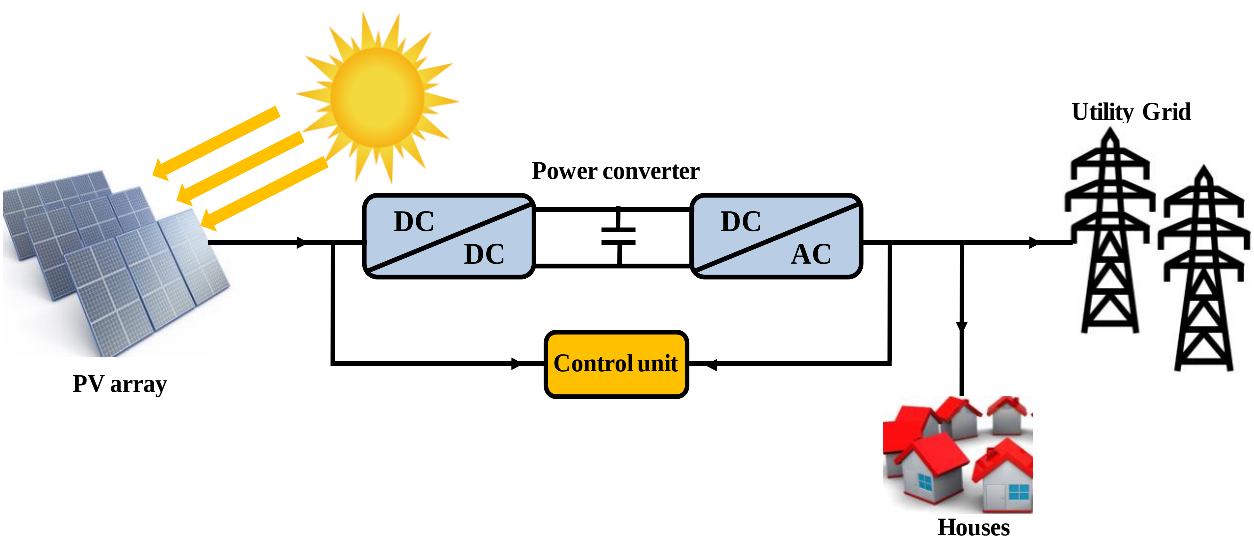

Figure I.6. Diagram of GCPV system.

I.3.3. Hybrid photovoltaic (PV) systems

Solar hybrid photovoltaic systems represent a pioneering methodology, integrating solar photovoltaic technology with one or more additional renewable energy sources like wind, hydro and diesel generator illustrate in figure I.4to create a more robust and dependable energy solution.

This encompasses a range of technologies that designed to augment efficiency and performance metrics. The primary purpose of these systems is to leverage the strengths of different renewable, whose generation patterns often complement each other, to ensure a more consistent power supply. For instance, solar energy has a peak output during daylight hours, while other renewable such as wind or biomass can generate power during cloudy periods, at night, or in different seasons, thereby reducing the variability in energy production.[14]

I.3.4. Performance and efficiency metrics in GCPV (Grid connected PV) systems

Power quality performance in grid-tied (PV) systems is the assessment and analysis of the quality generated by these systems.

The aim of this evaluation is to identify quality problems, such as those affected by voltage fluctuations, harmonic distortion, and flicker.

This analysis enables system operators to optimize performance, identify areas for improvement and take the necessary corrective action. Otherwise, an assessment of electrical quality is essential to ensure that systems and utility codes, here a sustainable and lasting promotion.[13]

The International Energy Agency (IEA) has established a set of performance parameters for photovoltaic (PV) systems, which are in accordance with the IEC 61724 standard.

Moreover, a database has been developed, enabling the reliable comparison of hundreds of systems. [13].

Three key parameters are used to assess the efficiency of PV systems:

I.3.4.1. Yields

Yields in photovoltaic systems are key metrics that measure the energy output and efficiency of the system.

- **Reference yield (Y_r)**

This parameter is defined as the theoretical amount of energy that a PV array could produce under specific ideal conditions. Mathematically, Y_r is represented as the ratio of the total inclination irradiance to the global irradiance at STC of (1000 W/m^2)[15]. It expresses the yield in terms of kWh/kWp/day or hours/day[10].

The Reference Yield can be calculated using the formula:

$$Y_r = \frac{H_t}{G_0} \tag{I.2}$$

Where: $\boldsymbol{H_t}$ is total inclination irradiance.

$\boldsymbol{G_0}$ is the reference irradiance of the array.

- **Array yield (Y_a)**

This metric measures the efficiency of the PV system in transforming the available solar energy into usable electrical energy. It is given by the ratio of the DC energy output generated by the system to its nominal power (P_{pv0}).[17]

The Formula:

$$Y_a = \frac{E_{dc}}{P_{pv0}} \tag{I.3}$$

Where:

$$E_{dc} = V_{dc} I_{dc} t \tag{I.4}$$

- **Final yield factor (Y_f)**

The final yield factor "Y_f" is the ratio of energy produced to that injected into the grid "E_{ac}" over time " a day "d", month "m" or year " and the nominal power of the PV array (P_{Pv0}) is calculated using the reference solar irradiance(1 kW/m^2) and temperature(25∘C). [12]

It can also be described as the number of operating hours a PV system must run at its rated power to deliver the same energy as at its peak power[10]. Y_f provides a convenient way to compare PV systems regardless of their size.

The final output is determined by the total energy actually produced by the system divided by the peak capacity of the system at a given time[9,12,13], as shown in the formula:

$$Y_f = \frac{E_{ac}}{P_{pv0}} \tag{I.5}$$

I.3.4.2.Efficiencies

Efficiencies in photovoltaic systems are critical for evaluating performance. Array Efficiency measures how effectively the PV modules convert sunlight into electricity, reflecting the quality of the solar cells and their operating conditions.

Inverter Efficiency assesses the inverter's ability to convert DC power from the array into usable AC power, with losses typically occurring during this process.

Transformer Efficiency is vital in grid-connected systems, as transformers step up voltage for transmission, and their efficiency indicates how well they minimize energy losses during this conversion. Together, these efficiencies determine the overall system performance and energy output.

Array efficiency

An essential parameter assesses a photovoltaic system's ability to convert sunlight into electrical energy. It represents the efficiency of photovoltaic (PV) modules and generally expressed as the ratio between the electrical energy generated by the panel and the incident solar energy, normalized for ideal conditions.

The array efficiency can be calculated using the formula:

$$\eta_A = \frac{E_{dc}}{H_t A_a} \times 100 \tag{I.6}$$

- η_A: This represents the array efficiency.
- E_{dc}: This is the DC output energy generated or delivered by the panel, expressed in kilowatt-hours (kWh).
- A_a: This measurement can indicate the surface area of the panel that is actually used to generate energy, contributing to overall efficiency.
- H_t: This refers to total solar irradiation, expressed in kilowatt-hours per square meter (kWh/m²). This indicates the total amount of available solar energy that can be captured by photovoltaic panels over a specific period

Inverter efficiency

The efficiency of the inverter is defined as the ratio of the amount of alternating current (AC) that it produces to the amount of direct current (DC) that it receives from the photovoltaic panels. The inverter efficiency is therefore a measure of the inverter's performance in converting the DC generated by the photovoltaic panels into the AC that can be used by the electrical grid.

High inverter efficiency is essential to minimize energy a loss during conversion. The calculation of the inverter efficiency is achieved through the implementation of the following formula:

$$\eta_{inv} = \frac{P_{ac}}{P_{dc}} \times 100 \qquad (I.7)$$

Where:

- P_{ac} is the AC output power, **&** P_{dc} is the DC input power.

System efficiency

In the context of energy conversion systems analysis, it is essential to consider the system efficiency.

When assessing the performance of photovoltaic systems, it is vital to consider system efficiency as a critical factor. It shows how well the system can turn sunlight into usable electricity.

The calculation of the system efficiency is to be conducted in accordance with the following formula:

$$\eta_s = \frac{E_{ac}}{A_a \times H_t} \times 100 \qquad (I.8)$$

Where:

- η_S: This represents the system efficiency.
- E_{ac}: This is the AC output energy generated or delivered to the electrical grid, expressed in kilowatt-hours (kWh).
- A_a: This measurement can indicate the surface area of the panel that is actually used to generate energy, contributing to overall efficiency.
- H_t: This refers to total solar irradiation, expressed in kilowatt-hours per square meter (kWh/m²).

This indicates the total amount of available solar energy that can be captured by photovoltaic panels over a specific period.

I.3.4.3. Quality factors

Quality factors are essential metrics used to assess the system's performance, reliability, and overall effectiveness.

These factors play a crucial role in pinpointing areas for improvement and ensuring the system operates at its highest potential, the key quality factors to consider:

Performance ratio P_R

This is an essential metric that assesses the efficiency of the PV plant by comparing its actual output to the expected output under optimal conditions.[15]

The P_R reflects how effectively the PV system operates relative to its potential, considering losses resulting from environmental factors, system inefficiencies, and operating conditions.[18]

It is a dimensionless quantity defined as the ratio of final to reference energy yields:

$$P_R = \frac{Y_f}{Y_r} \times 100 \ (\%) \tag{I.9}$$

- **Capacity utilization factor (CUF)**

It is another performance metric used to evaluate the efficiency of a power generation system, such as a photovoltaic (PV) plant.[17]

It is evident that when a system functions in a manner that consistently generates the maximum energy possible, in accordance with its installed capacity, the capacity factor is equivalent to one.[19]

$$CUF = \frac{Y_f}{P_{nom} \times 365 \times 24} \times 100 \ (\%) \tag{I.10}$$

I.4. Losses

In photovoltaic (PV) systems, "losses" are reductions in energy output that occur due to various factors during the overall process of energy conversion and production.

These losses can significantly affect the overall efficiency and performance of a PV system. The main types of losses that typically occur are:

I.5.1. Radiation losses

In photovoltaic (PV) systems refer to the portion of solar energy that is not converted into electrical energy due to various factors. These losses occur because not all incoming solar radiation can be captured and utilized by the PV modules, the main causes of radiation losses:

- **Partial shading**

If part of the PV array is shaded, the overall energy output is reduced.

- **Inhomogeneous irradiance**

Variations in sunlight intensity within the array can result in inefficiencies.[8]

- The term 'L_C capture losses' is used to refer to the difference between the optimal amount of solar energy that the panel should ideally receive (Y_r) and the amount actually captured during operation (Y_a).This formula pertains to loss-capture within a photovoltaic system. The term "L_C" is used to denote "loss-capacity" and is expressed as: $L_c = Y_r – Y_a$. (I.11)

Where:

- L_c: Capture losses.
- Y_r: Reference yield.
- Y_a: Array yield.

I.5.2. Thermal losses

These losses occur due to the temperature of the solar module. If the temperature of the module exceeds 25 °C, the efficiency is reduced.[12]

I.5.3. Electrical losses

These losses reduce the overall efficiency and energy output of the system. Here are the main types of electrical losses and their causes:

- **Line losses:** Resistance in the line causes energy to be lost as heat.
- **Inverter losses:** When converting DC power to AC power, efficiency losses occur due to inefficient inverters.[8]
- These losses can be calculated by the following formula: $L_s= Y_a - Y_f$ (I.12)

Where:

- L_s: Losses system.
- Y_a: Array yield.
- Y_f: Final yield.

I.5.4. Contamination losses

The reduction in energy output caused by the accumulation of dirt, dust, pollen, bird droppings, or other debris on the surface of the PV modules. Dirt and debris accumulation on PV panels can block sunlight and reduce system performance. These contaminants block sunlight from reaching the solar cells, reducing the system's efficiency and energy production. Cleaning and maintenance can help reduce these losses.[8]

I.5.5. Mismatch losses

The differences in the electrical characteristics (e.g., current, voltage, or power output) between PV modules or strings connected in series or parallel can lead to mismatch losses. These differences arise due to factors such as manufacturing variations, shading, soiling, degradation, or temperature variations. Mismatch losses reduce the overall efficiency and energy output of the system, resulting in poor overall performance.[8]

I.5.6. Other losses

In addition to mismatch losses, photovoltaic (PV) systems experience several other types of losses that can reduce their overall efficiency and energy output.

These losses can be due to a variety of factors, such as, for example, low irradiance, shading, glass reflection losses and dust accumulation on the modules, misalignment, and wiring losses. [8,12]

I.6. Understanding and addressing faults in photovoltaic systems

Photovoltaic (PV) arrays and cells are delicate devices that need to be placed in open spaces to absorb as much sunlight as possible. However, constant exposure to the environment subjects them to various physical and weather-related stresses throughout the year. Over time, this can lead to problems such as corrosion, cracking and disintegration, all of which reduce their efficiency.

Because PV cells rely on sunlight to generate electricity, any obstruction - such as shading - can cause serious problems. Even partial shading can cause an imbalance in the electrical characteristics of the system, leading to overheating and potential damage to the cells.

In addition to environmental challenges, electrical faults are a common problem in PV systems. These are often the result of poor or loose connections between conductors or faulty soldering at joints. Such defects, along with other types of system failure, reduce efficiency and limit power output. If not addressed in time, they can lead to energy losses and a reduction in overall system to ensure that the system operates efficiently and safely, it is essential that these faults are detected and repaired as early as possible. Predictive maintenance and proactive fault detection play a crucial role in preventing failures, reducing power losses and maintaining high quality energy output.

I.6.1. Classification of photovoltaic faults

It is possible that faults will occur in PV systems across a variety of components, from individual modules to the broader system infrastructure. In order to understand the different types of issues that can arise during operation, and to help improve the reliability and efficiency of the system, it is important to be able to classify faults in photovoltaic (PV) systems.

Where possible, faults in PV systems can generally be categorized based on their nature and the location within the system where they occur[20]. The figure I.7 shown that PV system failures are categorized into three distinct types: physical faults, environmental faults and electrical faults. The former are defined by impairment to PV panels, with examples of this being cracks and internal defects in cells and diodes.

The second pertain to external factors, including, but not limited to, shadowing from trees, accumulation of dirt and meteorological phenomena, for example clouds.

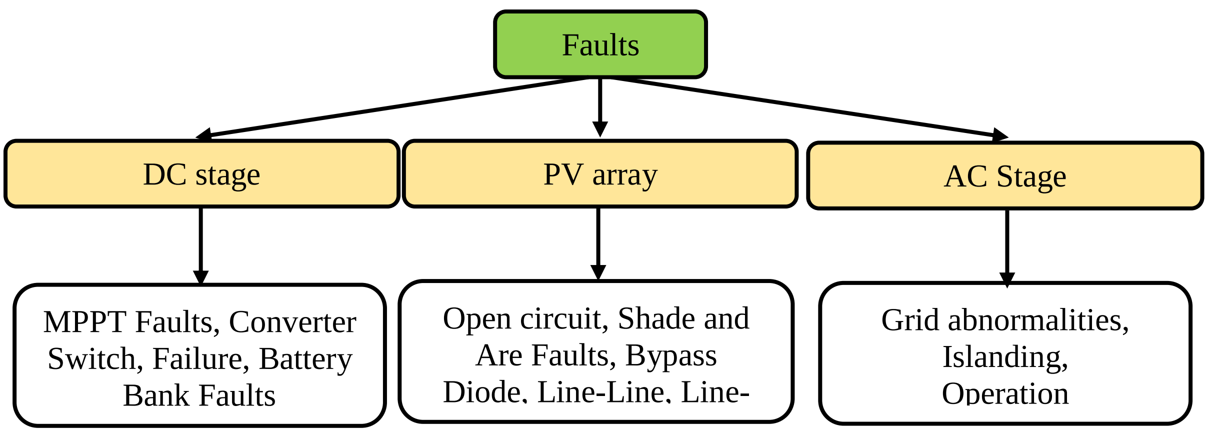

Figure I.7.PV system faults classification.

The latter pertain to electrical faults which can be classified into three distinct classifications: array faults, DC-side faults, and AC-side faults (Figure I.7) [21]. The standard configuration of a photovoltaic system comprises two distinct stages: the voltage step-up stage and the inverter stage. Alternatively, the system can be viewed in terms of the DC and AC stages.

- **Array faults**: refer to malfunction in a photovoltaic system that can affect the overall performance of interconnected solar modules. These failures can be caused by shading fixed obstacles such as trees or buildings, or temporary factors such as clouds or debris[22]. Defective cells, such as those that are burned, cracked or damaged, can lead to a decrease in energy production. Connection failures are usually the result of defective connections between the modules, which can cause short circuits or open circuits and interrupt the system function.[23]

Performance differences between modules can also lead to failures, which may be due to manufacturing variations or operating conditions.

In addition, thermal failures, including the emergence of hot spot [24] caused by defective cells, dirt accumulation or snow covering[25], may result in overheating and damage to the module. It is crucial to detect and intervene early to avoid these problems and ensure the longevity and efficiency of the photovoltaic system.

- **DC-side faults:** can have considerable ramifications for its performance and energy efficiency. Inverter switching failures, attributable to issues with IGBTs or MOSFETs, result in current flow interruption and consequent reduction in energy conversion efficiency. Faults in the maximum power point tracking (MPPT) system impede the optimization of energy extraction by erroneously adjusting the operating point in response to sunlight variations, thereby diminishing electricity production.[26,27]

Battery bank failures, typically resulting from abnormal conditions such as overcharging or over discharging, compromise battery efficiency and pose safety hazard.[28] Blocking diode failures enable the passage of undesirable current through PV modules, while bypass diode failures hinder panels from safeguarding against over-currents[29].Open circuit failures, often attributable to faulty connections or deteriorating seals, completely obstruct the flow of current, compromise system operation[28,30].Although these failures are infrequent, their detection and resolution are paramount for optimal system performance.[31,32]

- **AC-side faults**: It is important to note that faults in photovoltaic (PV) systems on the alternating current (AC) side have the potential to result in a number of issues. Inverters, which are vital for converting direct current (DC) to AC for grid injection, may be particularly susceptible to certain problems[33]. Internal component failures in inverters, such as control circuits, capacitors, and power transistors(IGBTs and MOSFETs) [34], can have an impact on their efficiency in current conversion.

Additionally, challenges with control and software management can further add to these concerns. Power quality problems, including voltage sags, swells, transients, spikes, harmonics, and imbalances, can also have an impact on both system and grid performance, as well as potentially causing damage to equipment. Failures in protection and safety devices, such as protective relays and circuit breakers, have the potential to jeopardize the safety of the entire system in the event of a failure.

Therefore, it is recommended that these faults be addressed in order to ensure the smooth operation and safety of PV systems.

I.7. Conclusion

This chapter has provided an overview of photovoltaic (PV) systems, its different types based on their functionality and integration with the electrical grid. Where we discuss in detail the grid connected PV systems, their components, performance and efficiency metrics. We have had the opportunity to consider the various challenges and losses that have the potential to impact system efficiency. In addition, we have explored different faults that may be involved in the system, the latest strategies for fault detection and diagnosis in PV systems and an overview of protection within Electrical Networks. The comprehension of these concepts is essential for the appreciation of the potential of photovoltaic technology in achieving global energy sustainability while addressing environmental concerns. This chapter lays the foundation for a deeper exploration of PV technology and its applications in modern energy systems. In the next chapter, we will present the Ain El-Melh photovoltaic (PV) solar power plant.

Chapter II

″Presentation of the Ain El-Melh photovoltaic solar power plant"

II.1. Introduction

The Ain El-Melh photovoltaic power plant, located in the wilaya of M'sila, is an essential infrastructure for the production of solar energy in Algeria. The project is part of the national strategy to develop and harness renewable resources, thereby reinforcing the country's energy transition.

The facility uses photovoltaic panels to convert solar energy into electricity. Thanks to this clean, inexhaustible source of energy, it makes an active contribution to reducing CO_2 emissions, offering a sustainable solution for a more environmentally friendly future.

With its significant production capacity, the Ain El-Melh photovoltaic power plant will efficiently supply the M'sila region while meeting the country's growing energy demand. This emblematic project represents a strategic step forward in the diversification of Algeria's energy mix, facilitating the integration of renewable energies into the national grid.

This chapter aims to explore Sonelgaz-ER’s (Sonelgaz-Energies Renouvelables) role, the plant’s technical features, and its broader impacts.

We describe its fundamental role in the development of the national energy sector, before focusing on the Ain El-Melh photovoltaic plant.

An in-depth analysis will highlight its technical characteristics, economic challenges and environmental impact, illustrating its contribution to the country's energy transition.

II.2. Energy landscape in Algeria: Context for Sonelgaz-ER’s efforts

Energy in Algeria is dominated by heavy hydrocarbon dependence with oil and natural gas, representing more than 90% of the country's total exports.

This situation makes the Algerian economy vulnerable to fluctuations in global oil prices, as evidenced by the fall in revenues that have followed the decline in barrel prices since 2014. This dependence has led the government to recognize the need to diversify the economy and move toward renewable energy sources.

- **Economic dependency on hydrocarbons**

The Algerian economy is mainly based on hydrocarbons, which creates vulnerability when prices fall in the market. This situation calls for reflection on the need for an energy transition and the development of renewable energies to ensure long-term energy security.

Energy demand and consumption

Algeria's energy consumption has been on a stable increase, which is mainly inspired by population growth and increasing industrial activities. Power consumption, in particular, in recent years, require increased power generation capabilities. This increasing demand underlines urgency for the creation of more durable and reliable energy systems.

Government initiatives and policy framework

Recognizing the challenges represented by its dependence on hydrocarbons, the Algerian government has begun several policies to promote the development of renewable energy. The national strategy includes ambitious goals for renewable energy, aiming at the installation of approximately 22,000 MW of renewable capacity by 2030. This strategic view seeks to reduce fossil fuel dependence, promote environmental sustainability and increase energy safety.

Role of Sonelgaz-ER in the energy transition

In this context, it plays a vital role within Algeria's energy transition strategy. As a key player in the electricity sector, the subsidiary of Sonelgaz is tasked with several critical functions:

- **Investment in renewable energy:** It has been fundamental in the integration of renewable sources with Algeria's energy mix, especially through the implementation of photovoltaic solar projects and wind energy. This aligns with national objectives to increase the contribution of renewables and mitigate greenhouse gas emissions.
- **Infrastructure development:** By improving infrastructure in needy regions, particularly in southern Algeria, Sonelgaz-ER helps provide stable supply of electricity to remote communities, promoting economic and social development.
- **Innovation and training:** Through partnerships for technical training and adoption of modern technologies, Sonelgaz-ER contributes not only to operational efficiency, but also to training in the local workforce. This focus on innovation is essential for the transition to a knowledge - based renewable energy sector.

Environmental and economic implications

Sonelgaz-ER 's commitment to renewable energy is not only about meeting regulator or market demands; it also represents a strategic step towards stability.

By investing in renewable, Sonelgaz-ER is helping prevent environmental effects associated with fossil fuel dependence, such as air pollution and climate change. In addition, there is possible economic benefits in diversifying energy mixture, including employment generation and long - term energy value stability within the renewable region.

II.3. Sonelgaz-ER overview

II.3.1. History

The Société de Production d'Électricité d'Algérie (Sonelgaz-ER) was created on the 7th April, 2013, as part of the Sonelgaz Group.

This company emerged from the division of the Energy Production Company « Société de Production d'Énergie (SPE) », headquartered in Ghardaïa, Algeria. This was all part of the greater energy production enhancement projects that Algeria has initiated for itself, especially directed toward the renewable sector, in the face of decreasing oil revenues and the search for energy diversification.[35]

II.3.2. Mission

Sonelgaz-ER has several core missions:

- **Electricity production**: The company focuses on generating electricity through renewable energy, which mainly situated in high climatic plateau in Algeria.

Its purpose is to support the infection planned to clean energy sources, it aligns with the country's ambitious target of generating 22,000 MW renewable energy by 2030.

- **Infrastructure development:** It is responsible for developing and maintaining electrical infrastructure, particularly in the southern regions of Algeria.

- **Engineering and management:** Sonelgaz-ER supervises engineering, maintenance and management of its electrical generation facilities, ensuring efficient operation and service provision, managing the sale of energy generated to various distribution subsidiaries, especially SDO (Société de Distribution d'Électricité de l'Ouest) and SDC (Société de Distribution d'Électricité de la Centre).

- **Commercialization of energy:** The company is involved in marketing the energy produced, which contributes to the overall energy market in Algeria.[1,2]

II.3.3. Achievements

From its establishment in 2013 through 2017, Sonelgaz-ER has made significant progress:

- **Installed capacity growth:** Company's installed capacity tripled from 2013 to 2017, reaching 1,134.73 MW until the end of this period. This growth occurred mainly due to the addition of renewable energy capabilities, along with conventional plants.
- **Energy production:** In the same period, Sonelgaz-ER enhanced its energy production capabilities, producing over 1,555 GWh of electricity by 2017, of which a growing part came from renewable sources such as solar and wind,.
- **Renewable energy projects:** Sonelgaz-ER invested in solar photovoltaic and wind energy projects, leading to a substantial installed capacity of renewable energy that included:

❖ A significant number of solar power plants contributed to an installed capacity of 354 MW by 2017.

❖ Integration of wind energy projects into the production portfolio.

- **Environmental impact:** The company was fundamental in reducing carbon emissions, having avoided more than 602,000 tons of CO_2, using renewable energy sources. In addition, the gas and fuel economy of renewable energy generation exemplifies its contribution to environmental sustainability.
- **Technical training:** According to its mission, Sonelgaz-ER has also focused on local personnel training in advanced technologies, collaborating with institutions in China and Germany to improve skills in renewable energy technologies.

The figure II.1 illustrated Photovoltaic power plants in Algeria under the management of Sonelgaz-ER.

Figure II.1. Photovoltaic power plants in Algeria under the management of Sonelgaz-ER.

II.4. Ain El-Melh PV plant

II.4.1. Location and climatic conditions

Ain El-Melh's photovoltaic plant is located in the M'sila region of Algeria, as shown in Figure III.2 it is an area characterized by unique climatic factors such as temperature fluctuations and variations in solar irradiance, which affects PV performance on average 5.5 to 6 kW/m²/day. The installation was officially commissioned on September 24, 2017, the station is located in an area of 40 hectares and produces more than 100 MWh of electricity, on average per day, with an installed capacity of 20 MW. The photovoltaic plant reached a final yield ranging from 3.99 h/day in December to 5,897 h/day in April, illustrating the impact of seasonal climate variations on energy production. In 2019, Ain El-Melh's PV factory provided 827.9 MWh to the grid, with an annual capacity factor ranging from 16.65% to 24.57% under high climatic plateau conditions. This strategic location makes ideal for solar energy production, capitalizing the abundant sunlight to maximize production. The plant serves a crucial function in Algeria's renewable energy strategy, contributing to the country's efforts to reduce its dependence on fossil fuels and increase the proportion of clean energy in its energy mix. By taking advantage of solar energy in this region rich in sun, the installation supports the larger objectives of sustainability in Algeria and increases energy safety. [2,3]

Figure II.2. Aerial view of the Ain El-Melh 20 MWp solar (photovoltaic) power plant.

II.4.2. Description of the 1 MW subfields

1 MW sub-field in the photovoltaic system are organized settings of sunscreens designed for efficient power generation and management.

Here is a detailed description based on the information provided:

- **Sub-field Setup:** Each 1 MW sub-field consists of two identical 500 kW sub -campaigns, forming part of the largest matrix of photovoltaic plants. Each subfield contains modules arranged to optimize energy production.
- **Module arrangement:** A 1 MW sub-field comprises 80,080 poly-crystalline modules (250 WP each). Focusing on a 500 kW sub -Camp, it includes 968 modules, organized as 22 sequence modules in 44 strings for efficient power management.

The modules are installed at a southern 33 ° slope angle to maximize sun exposure throughout the day.

- **Electrical components:** Each sub-field connects to a 500 kW SUNGROW inverter (input: 500–850 VDC, output: 315 VCA), paired with a shared 1250 kVA step transformer to raise the voltage to the grid transmission.[15]
- **Cabling system:** It has a hierarchical cabling system with:
  - 11 level 1 junction boxes
  - 3 level 2 junction boxes
  - 1 level 3 junction box

This design minimizing DC cable lengths, reducing resistive losses and relieving maintenance.

- **Evacuation of power:** Electricity is evacuated by 60 kV airlines, connecting to the national network.
- **Reproducibility of efficiency and design:** Uniform design in sub-fields ensures consistent energy flow through inverters and transformers, increasing operational reliability and efficiency.

This structured approach to design, operation and maintenance.

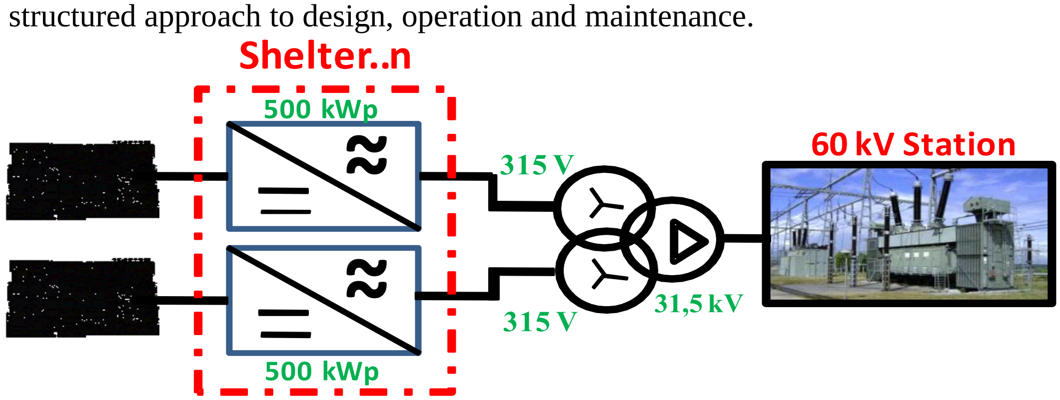

Figure II.3. Overview of the 20 MW Ain El-Melh grid connected power plant.

II.5. Equipment details

The equipment used at the Ain El-Melh photovoltaic solar power plant includes various components needed to produce, convert and distribute solar energy.

Specific features may vary depending on the design and requirements of the plant, but here is an overview of the equipment often found in solar photovoltaic plants such as the one at Ain El-Melh:

II.5.1. Solar panels (Photovoltaic modules)

As illustrated by the solar panels shown in Figure II.4, the conversion of solar energy into electricity is possible by the presence of photovoltaic cells made of silicon or other semiconductor materials. These modules characterized by high efficiency are configured in an array on the site to customize the possession of solar radiation.

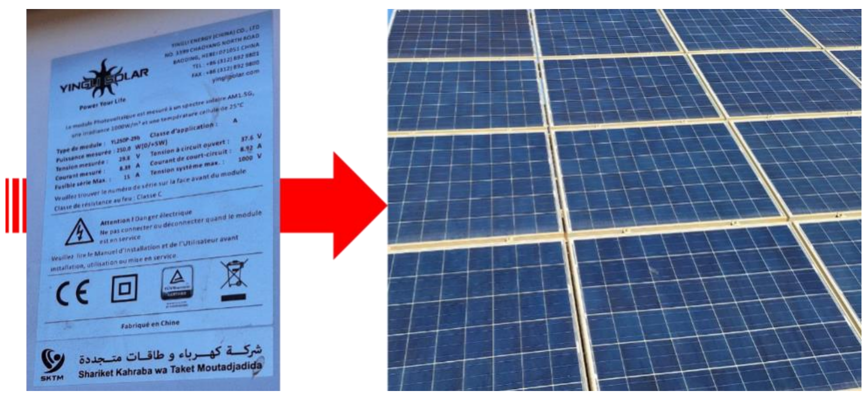

Figure II.4. Photovoltaic panels used in Ain El-Melh power plant

II.5.2. Inverters

Inverter is an electronic device that changes the direct current produced by photovoltaic modules through control and safety circuits. It is capable of accepting the maximum current and voltage produced by the photovoltaic area. Figure II.5 shows the 500 kW solar inverters used in the installation.

Efficiency is the ratio of output power for input power, which is expressed as a percentage. The high temperature reduces the efficiency of the inverter. This conversion could potentially contribute to providing consumers with electricity, while also ensuring efficient and stable energy production.

The power plant is equipped with 40 kW DC/AC, 2 per subfield -made Sun-grow brand inverter. The input range of .520-820 VDC ensures the stability of AC output voltage with a maximum current of 1008 A at high efficiency of 98%. The DC side of the inverter consists of 4 bipolar inputs, each of which is equipped with DC fuse, a general disconnect switch and a DC lightening arrests. The technical specifications of the inverter are given in Table II.1.

Table II.1. Technical Specifications of the inverters.

Inverter	**Specification**
The Brand	SUNGROW
Type Of	SG500MX
Operating Temperature	-30 C / 50 C
IP Protection	
DC Output	
Max Voltage	1000V
Isc	1344A
Voltage V_{mppmin} (minimum voltage at maximum power point)	500V
Voltage V_{mppmax} (maximum voltage at minimum power point)	850V
Max Input Current	1120A
Overvoltage Category	II
AC Output	
Rated Output Power	500KW
Rated Output Voltage	3-315V
Rated Output Frequency	50Hz
Max Output Current	1008A
Power Factor	-0.9/0.9
Overvoltage Category	///

Figure II.5. Solar inverter 500 KW.

II.5.3. Mounting structures

A variety of structural designs are employed for the purpose of supporting solar panels, including integrated fixed, adjustable and systems with solar trackers. For example, in Ain El-Melh power plant, fixed systems are used. The configuration of these structures is adapted to ensure maximum risk to sunlight, which increases the energy efficiency of the plant.

II.5.4. MW step-up transformer

To increase the electric voltage produced by PV systems before grid transmission, transformer units are employed. Transformers play an important role in integrating solar energy in the prevalent electrical infrastructure. Second-hand transformers represent state-of-the-art machinery, which is carefully commissioned by Sonelgaz-ER (Figure II.6 below shows the transformers used in the 400V, 30kV and 60kV power plant). His implementation required adequate capital expenditure due to his complex nature of his manufacturing processes. In addition, monitoring and maintenance of these transformers require considerable expenditure. In addition to replacement, maintenance and expenses associated with a solitary unit disadvantage-work, service can cause disintegration and adequate revenue loss. The loss of a single unit can cause a significant loss of revenue. In particular, in the context of AC transformer and transmission system, it is mandatory to accept the important role of these transformers in the domains of electrical infrastructure. The primary function of these transformers is to convert low voltage (LV) power into high voltage (HV) power. Transformers are engaged within a shelter envelope, which is equipped with heat radiation fans on four sides, working according to the temperature. As displayed in Table II.2, the technical features of transformers purchased by Sonelgaz-ER Company are as follows.

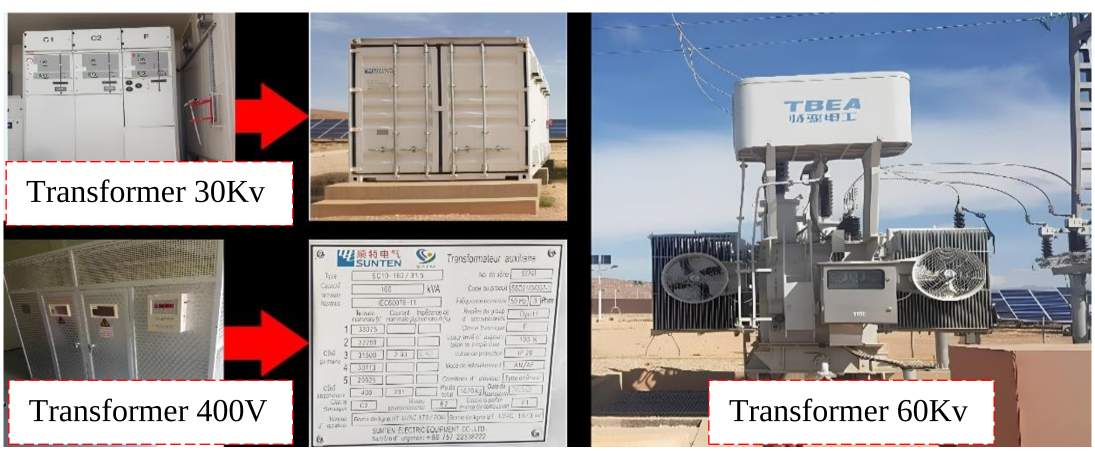

Figure II.6. Different Transformers.

Table II.2. Technical Specifications of the transformer.

The Brand	SUNTEN
Type Of	ZBW10N 1250/31.5/0.315-0.135
Rated Capacity	1250KVA
Rated Voltage	31.5KV /0.315KV
Rated Frequency	50Hz
Aspect Dimensions	4700*2438*2896mm
Cooling Mode	AN/AF
Rated Input Voltage	315V/315V
Rated Input Current	1146/1146
Rated Output Voltage	30000V
Rated Output Current	24.1A

II.5.5. Switchgear and protection devices

The installation switchgear is equipped with circuit breakers and protective equipment, which is a careful engineer to ensure the integrity of the system. These components are designed to prevent potential risks of electrical surcharge or malfunction (Figure II.7).

Figure II.7. Protection equipment.

II.5.6. Grid connection cabinets

The connecting cabinets of the Ain El-Melh photovoltaic plant, also known as string combinatory boxes, play a key role in collecting and monitoring direct current output (DC) of solar panel strings before being transmitted to inverters[37], (Figure II.8. shows grid connection cabinet at the Ain El-Melh photovoltaic power plant). One cabinet contains eight strings; each string has 22 solar panels.

Each cabinet is equipped with a digital control module, mounted on a DIN rail, which monitors the main parameters such as voltage, current and power.

These modules, usually with digital displays, allow real -time diagnostics and performance analysis.[38]

Cabinets also include circuit breakers, fuses, and outbreaks, ensuring safety and reliability.[39] Strategically positioned at the 40 -hectare site, they optimize energy collection and reduce losses, supporting the average daily production of over 100 MWh and an annual capacity factor from 16.65% to 24.57%, depending on seasonal weather conditions.

The use of these offices aligns Sonelgaz-ER 's commitment to adopt modern technologies, as described in its mission to innovate and train local employees, contributing to the national goals of 22MW of renewable energy by 2030.[4]

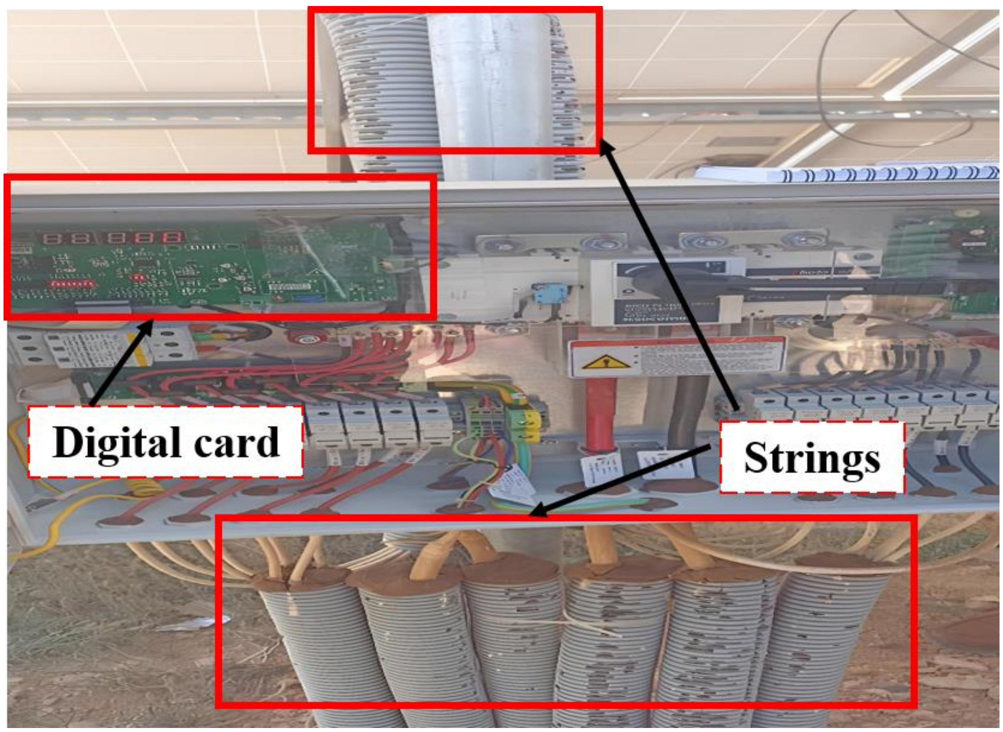

Figure II.8. Grid connection cabinet for the photovoltaic power plant of Ain El-Melh.

II.5.7. Measuring devices used in the Ain El-Melh station

Ain El-Melh Station is equipped with sensors equipped with meteorological monitoring stations to collect data on the main environmental parameters, as shown in Figure.II.9 solar radiation, temperature sensor, humidity sensor, anemometer, rain gauge and power protection.

The data collected is recorded in one of the factory data acquisition computers installed in the control room and this information is used to adapt to system performance and improve energy production forecasts.

Figure II.9. Meteorological Station.

II.5.7. Control room

A range of monitoring equipment is used to ensure real-time monitoring of plant performance. This includes monitoring energy production, analyzing system efficiency and detecting any anomalies.

The control room is a space that facilitates the work of engineers to monitor and control the efficient operation of all station equipment (inverters, panels, transformers, connectors, etc.). Data are collected and displayed on a sophisticated computer with an integrated technological programmed, Figure II.10. It also monitors meteorological data such as solar radiation (G), ambient temperature (Ta), device temperature (Tm) and wind speed (v), which you send to the measuring devices Figure II.9.

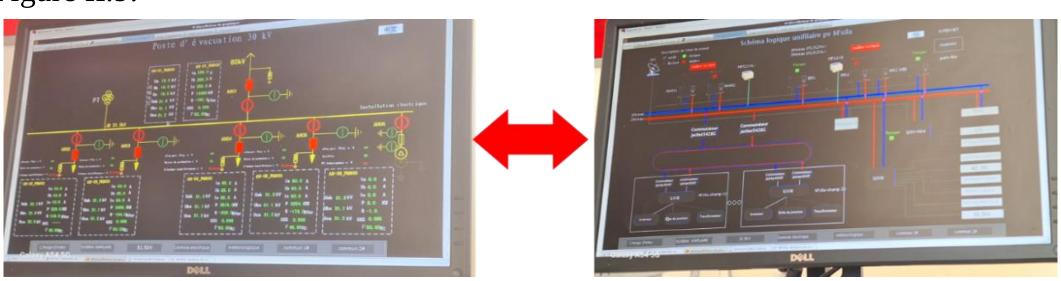

Figure II.10. Shows the optical sign diagram of the Ain El-Melh plant.

Every 15 minutes during the day. Control systems, whether software or hardware, play a crucial role in optimizing production, managing interactions with the grid and improving the safety and reliability of the installation.

II.5.8. Security and surveillance systems

At the Ain El-Melh plant, a solar energy installation, safety and surveillance are maintained through an integrated system that combines meticulous technologies for registration and advanced real-time records.

A key component is the "Surveillance Journal" (Surveillance Log), a detailed diary that systematically documents security-related events with entrances such as "Date et Time" and "observations", ensuring a comprehensive historical record of activities and checks (Figure II.11. present Surveillance system in the evacuation station).

This traditional approach is improved by sophisticated digital systems, including a “Surveillance by analog parameters of production valves”, which displays real -time data on critical production components such as valves, vital for operational safety and failure detection. In addition, an interface “Meteorological Surveillance Station” Scraping Environmental Factors-How Temperature and Moisture-Trashing Meters and Graphs, allowing the plant to anticipate and mitigate climate-related impacts.

Together, these systems form a robust safety structure, mixing physical state-of-the-art physical documentation to protect plant infrastructure and ensure uninterrupted operation in its semi-arid environment.

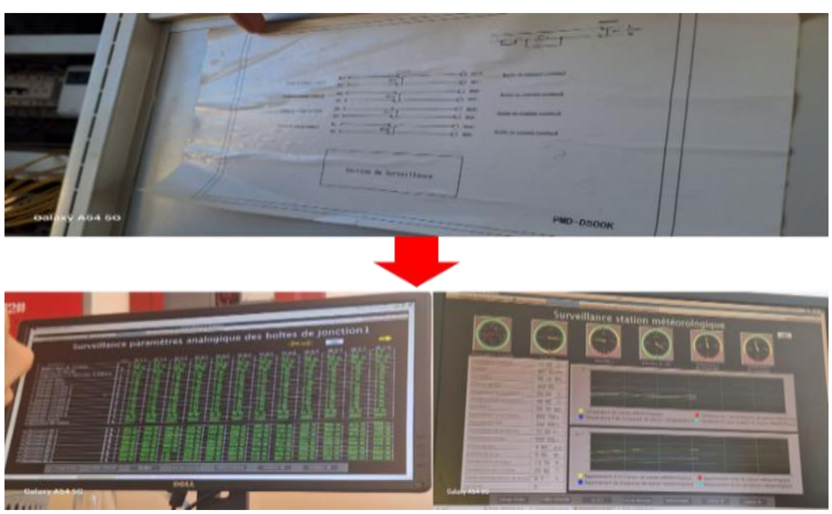

Figure II.11. Surveillance system in the evacuation station.

II.5.9. Auxiliary power systems (Optional)

To compensate periods of low sunlight or ensure the power supply to critical equipment, auxiliary systems such as storage batteries or emergency generators, they can be integrated into the installation. Figure II.12 shows the diesel generator installed in the photovoltaic plant.

Figure II.12. Diesel Generator.

II.5.9. Civil engineering works and infrastructure

The construction and operation of a photovoltaic power plant requires a wide range of civil engineering functions, including foundations, access roads, fencing and drainage systems. These elements ensure the stability and durability of the infrastructure.

All these components play an essential role in the optimal operation of the plant, contributing to the efficiency of energy production, the reliability of the system and its smooth integration into the electricity grid.

II.5.10. Solar panel cleaning methods

Maintaining the efficiency of photovoltaic panels in the Ain El-Melh plant is critical, especially considering the arid and dusty conditions of M'sila, where dust accumulation can reduce energy production by up to 10-15%. To face this challenge, the plant employs a systematic cleaning approach using specialized equipment.

As shown in Figure II.13, the plant uses a manual cleaning method involving a double tool, such as the Kärcher isolating system. This tool has two counter-root brushes that effectively clean the panel surface, removing dust and debris without scratching the glass.

The brushes are mounted on a long pole, allowing workers to clean the panels safely from the floor or high positions. Figure II.14 provides a wider view of the process, showing a technician in cleaning panels mounted on fixed structures, with water visibly helping to remove stubborn dirt. The Kärcher system is designed for efficient water cleaning, using low-pressure water jets to minimize waste, a critical feature in the water-scarce region of M'sila.

In Ain El-Melh, regular cleaning is essential to maintain 22% efficiency classification of the plant for its silicon polycrystalline panels, ensuring that the 20 MW installed capacity provides the expected 100 MWh daily output.

Figure II.13. Dual-brush cleaning tool (Kärcher iSolar) used for solar panel maintenance at Ain El-Melh.

Figure II.14. Technician cleaning solar panels, demonstrating the practical application of the cleaning system in the field.

II.6. Conclusion

Ain El-Melh photovoltaic power plant stands as the foundation stone of renewable energy ambitions of Algeria, which symbolizes the country's commitment to diversify its energy mixture and reduce its dependence on hydrocarbons.

Through the efforts of Sonelgaz-ER, a major player in the energy sector, the project not only exploits the abundant solar capacity of the M'sila region, but also contributes to environmental stability by cutting CO_2 emissions and promoting cleaner energy production. The technical sophistication of the plant-from its high efficiency photovoltaic modules to its strong grid integration-reflects Algeria's ability to adopt and innovate the ability of Algeria within the domain.

Financially, it supports energy security and regional development, while the grassroots work for a more flexible and durable future. As Algeria moves towards its target of 22,000 MW renewable capacity by 2030, the Ain El-Melh plant serves as a practical achievement and a symbol of widespread energy infections.

This chapter has underlined the decisive role of Sonelgaz-ER and the versatile contributions of the plant, which establishes the phase for the deepest discovery of its operational performance and long-term impact in later classes.

Chapter III

″ Performance Investigation of a Large-Scale Grid-Tied PV Plant: Case Study Ain El-Melh″

III.1. Introduction

Precise tilt radiation data are vital for the assessment of the photovoltaic systems (PV), with implications for critical metrics, such as reference yield (Y_r), array yield (Y_a), final yield (Y_f) and performance rate (P_R). In the PV Ain El-Melh 20 MW_P plant, a preliminary review of the 2019 data set revealed discrepancies in measured radiation (G_m).

These discrepancies are probably attributed to the misalignment of pyranometers, resulting in inaccuracies in the recorded data. These discrepancies resulted in underestimated irradiance values, particularly during the periods of peak sun exposure, distorting the performance evaluation of the plant. To address this, a correction methodology was adopted, using DC current data synchronized as a reliable actual exposure indicator.

This chapter aims to analyze the operational efficiency, energy yield, and overall effectiveness of the Ain El-Melh PV plant using the methodology employed to identify and correct these measurement errors, thus ensuring a robust performance analysis for the Ain El-Melh PV plant in 2019. The study seeks to enhance the understanding of large-scale PV plant operations in similar climatic and geographical conditions.

The findings will provide valuable insights with regard to the design, implementation and management of future PV installations.

III.2. PV Plant Description

The photovoltaic plant described in the study is a soil-mounted photovoltaic system connected to the grid, located in Ain El-Melh, Algeria. Here are the main features and details:

III.2.1. Capacity and configuration

- The plant has a total capacity of 20 MW_P and covers 40 hectares. It consists of 80,080 polycrystalline silicon modules, each classified at 250 W_P.
- The modules are organized in 40 sub fields, each with a capacity of 500 kW.

III.2.2. Technical specifications

- Photovoltaic modules have an efficiency of 15% and are installed with a southern 33° slope.
- Each sub-field is connected to a 500 kW sungrow inverter. The nominal power of the inverter is 500 kW and the transformers have an apparent power classification of 1250 kVA.

III.2.3. Electrical configuration

- Photovoltaic modules connect to inverters through various types of junction boxes categorized at different levels (level 1, level 2 and level 3).
- The system includes a climb transformer for efficient electricity transmission to the national network through 60 kV airlines.

III.2.4. Environmental factors

The geographical characteristics of the site include high solar potential, with an annual average of 7 kWh/m², moderate temperatures and low humidity, making it suitable for solar power generation.

III.2.5. Advantages of the place

The proximity of a 60 kV substation facilitates the efficient transmission of electricity generated to the national network, while the availability of enough land allows for a large -scale installation.

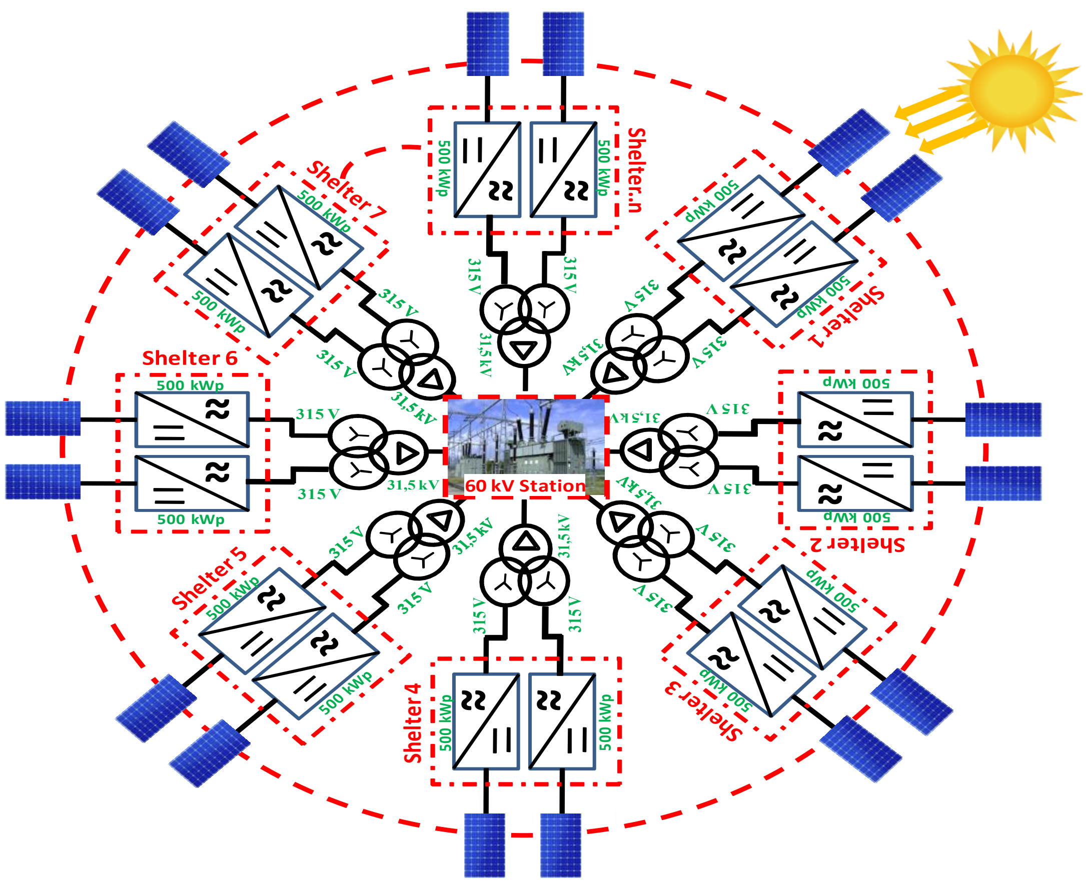

Figure III.1. Overview of the 20 MW Ain El-Melh grid connected power plant.

Figure III.2. Overview of the 20 MW Ain El-Melh grid connected power plant.

III.3. Analysis of real performance of the Ain El-Melh PV plant using 2019 Data

The section is related to monitoring the performance of Ain El-Melh Solar Photovoltaic Park, which has a capacity of 20 MW and is associated with the National Grid in 2019. The performance analyzed in this study follow the standards set by the International Energy Agency (IEA) and the standardized IEC 61724 is specified in the guide.

The chapter is structured into two main parts: the first focuses on analyzing the meteorological data collected from the Ain El-Melh site, while the second examines the daily performance of the photovoltaic field.

III.3.1. Analysis of meteorological data from 2019

Display of photovoltaic systems is directly affected by external factors, in which solar radiation is most important. Temperature variations also affect the efficiency of essential components. Factors such as wind speed and direction have less remarkable effect. Together, these factors shape environmental conditions in which a photovoltaic system operates. In order to better understand specific climate parameters in the Ain El-Melh region, data from various sensors was collected and analyzed during 2019.

III.3.1.1. Monthly insolation evolution

The evolution of monthly insolation refers to the variation in the amount of solar radiation received on a specific area over the months of the year. This variation is influenced by factors such as the Earth's tilt, geographical location, time of year, and atmospheric conditions.

To end this, an analytical study was performed to examine the solar radiation obtained by the photovoltaic module, in which measurements were recorded on the module tilt aircraft (IPOA) during year of 2019.

The analysis created significant ups and downs in radiation throughout the year. Radiation is an important factor in this context, as it determines the amount of solar energy available for conversion into electricity. As expected in the Algerian highland climate, the maximum recorded average monthly solar radiation is 8.93 kWh/m²/day during summer days and more precisely in June, while the minimum recorded is 5.09 kWh/m²/day during winter days (in December).

As depicted in Figure III.3, the radiation provides a comprehensive observation of the solar capacity of the presented measurement area, which facilitates evaluation of the efficiency of photovoltaic systems on specified periods. This information is important to increase understanding and customize the functioning of solar parks.

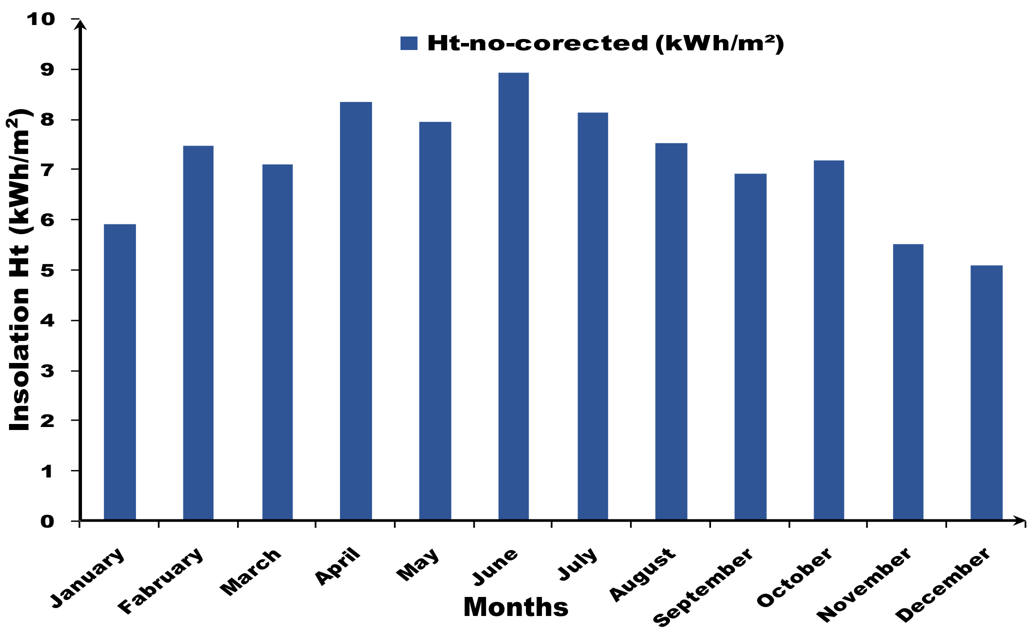

Figure III.3. Evolution of the average radiation of the Ain El-Melh PV power plant, (2019).

III.3.1.2. Evolution of monthly temperatures

As is illustrated in Figure III.4, the monthly temperature (ambient and modules) demonstrated ups and downs in year 2019. Monthly ups and downs in the temperature were seen, with an average of the environment from 1.1°C to 40°C. The temperature of the module displays the range between 70°C and 0,1°C.

It is noteworthy that the average monthly ambient temperature (Ta) influences the cell temperature (Tc), with both being critical in determining the operational efficiency of a PV system and cell temperatures generally increase with ambient temperature; however, factors like wind speed (Ws) can mitigate those increases by enhancing cooling, thereby improving PV performance.

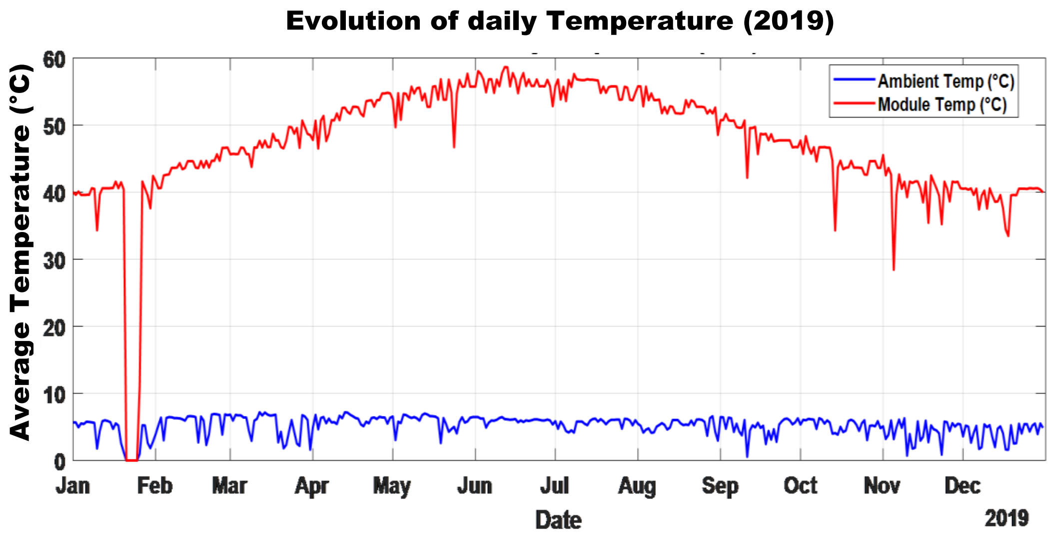

Figure III.4. Evolution of daily average temperatures at the Ain El-Melh PV plant.

III.3.2. Analysis of the performances of the Ain El-Melh PV power plant in 2019

Our performance analysis includes the photovoltaic field (Ain El-Melh) with a capacity of 20 MW on 2019. The field is connected to the grid at Ain El-Melh power station, which is located in the wilaya of M'sila.

III.3.2.1. Energy generated and energy delivered

As shown in Figure III.5, the monthly evolution of energy generated by the photovoltaic field (E_{dc}) and provided to the Distribution Network (E_{ac}) for the year of 2019 is illustrated. It is evident that the energy generated (E_{dc}) systematically exceeds the supplied energy (E_{ac}).

The maximum recorded average monthly energy generated is 2.92 kWh during spring days and more precisely in April, while the minimum recorded is 1.98 kWh during winter days (in December). In the other hand, the maximum recorded average monthly energy delivered is 2.85 kWh during spring days and more precisely in April, while the minimum recorded is 1.93 kWh during winter days (in December).

These energies demonstrate a consistent pattern with the Daily Sun (Ht), displaying a proportional relationship.

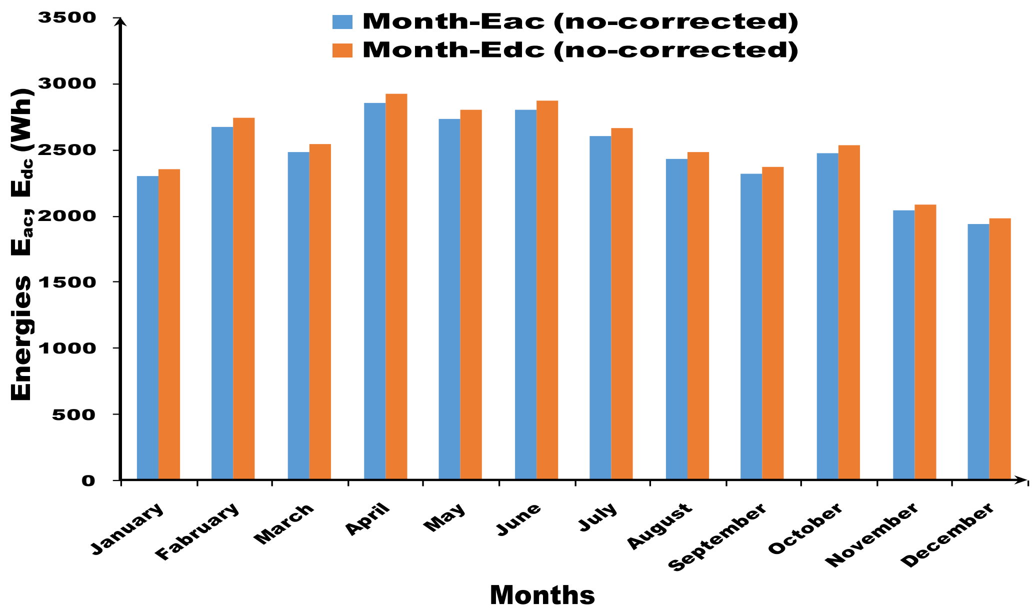

Figure III.5. Monthly evolution of the energies of the Ain El-Melh PV plant in 2019.

III.3.2.2. Reference yields, PV field efficiency and final yield

As illustrated in Figure III.6, the monthly progression of efficiencies for the year of 2019 is demonstrated, covering Reference Efficiency (Y_r), photovoltaic field efficiency « array yield » (Y_a) and final yield (Y_f) of the photovoltaic system.

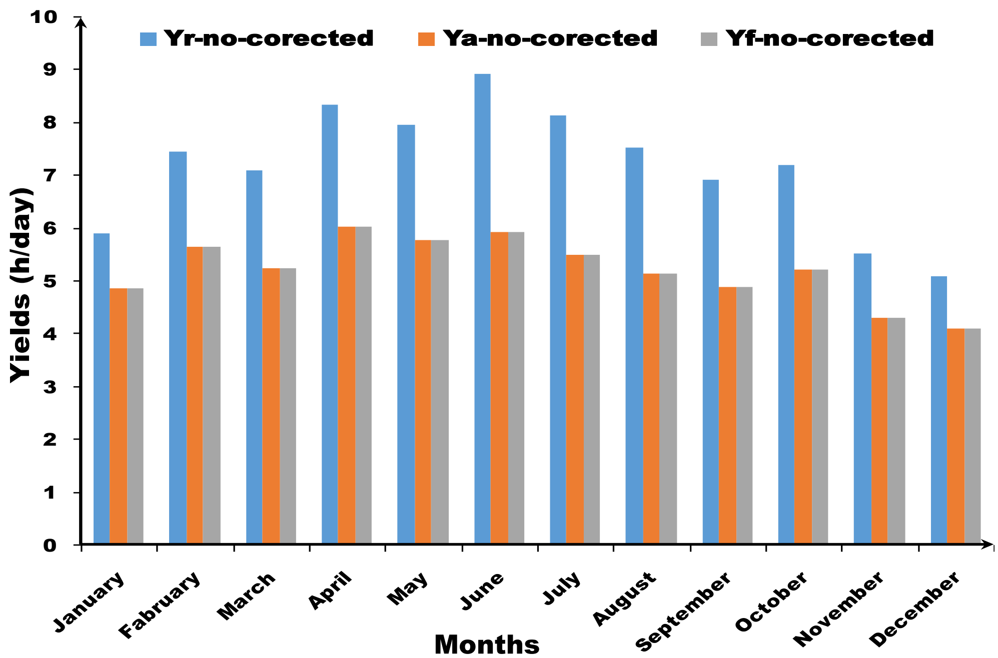

Figure III.6. Monthly evolution of different yields in the PV Ain El-Melh plant.

A discernible similarity in the tendency of these yields is evident.

The reference yield (year) displayed a monthly average range of 5.09 h/day for December to 8.93 h/day for June.

Photovoltaic field performance (Y_a) displays a maximum average of 6.04 hours a day on month of April, while experiencing a minimum of 4.09 hours a day on month of December, producing an average of 5.22 hours a month over the year.

Regarding the final yield, it reaches a maximum of 5.89 hours a day on the month of April and decreases to 3.99 hours a day on the month of December, producing an average of 5.12 hours a month over the year.

III.3.2.3. Performance ratio

As shown in Figure III.7, the monthly evolution of the performance ratio (PR) for the year of 2019 remained relatively stable, ranging from 64.8% on June and 81.19% on January. A performance rate greater than 80% means that the system is functioning close to its ideal efficiency under standard test conditions (STC).

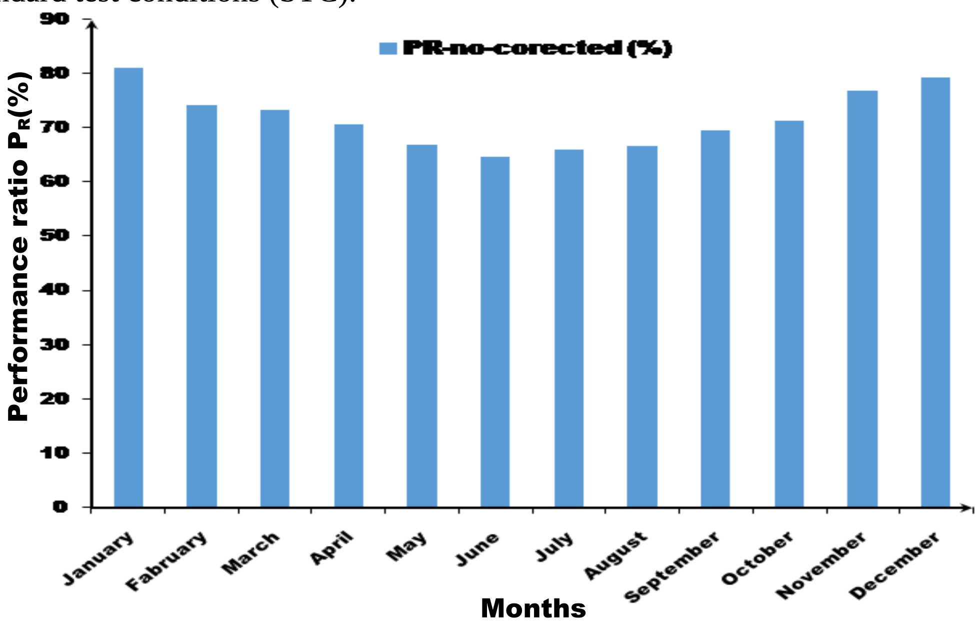

Figure III.7. Monthly evolution of the performance ratio of the Ain El-Melh PV plant.

III.3.2.4.Efficiencies

The figure.III.8 shows that in the month of January, a maximum array efficiency of 12.47% is achieved due to the weak cell temperature in other hand the minimum value observed in the of June by 10.29%.

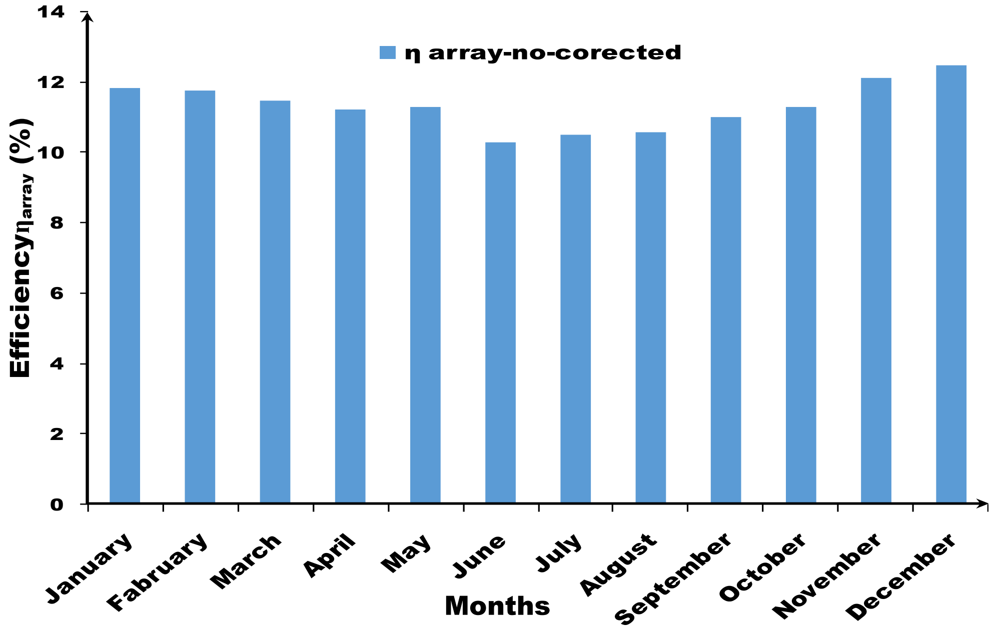

Figure III.8. Average monthly array efficiency.

The inverter's efficiency is affected by the in-plane variation of solar radiation [15,40] and the ambient temperature[15,41]. It is noted that the efficiency of the inverter remains stable with a recorded annual average of 97.64% (figureIII.9.).

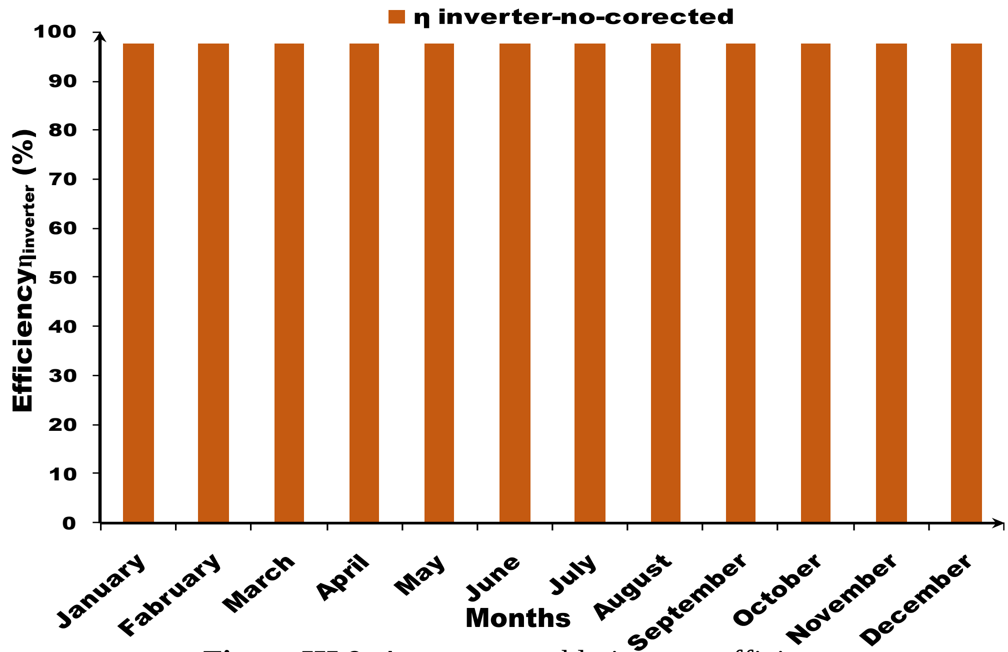

Figure III.9. Average monthly inverter efficiency.

The system efficiency is highest when both the array and the inverter are at their maximum efficiency. The system's maximum efficiency is 12.18%, which is recorded in winter "December" (figureIII.10.).

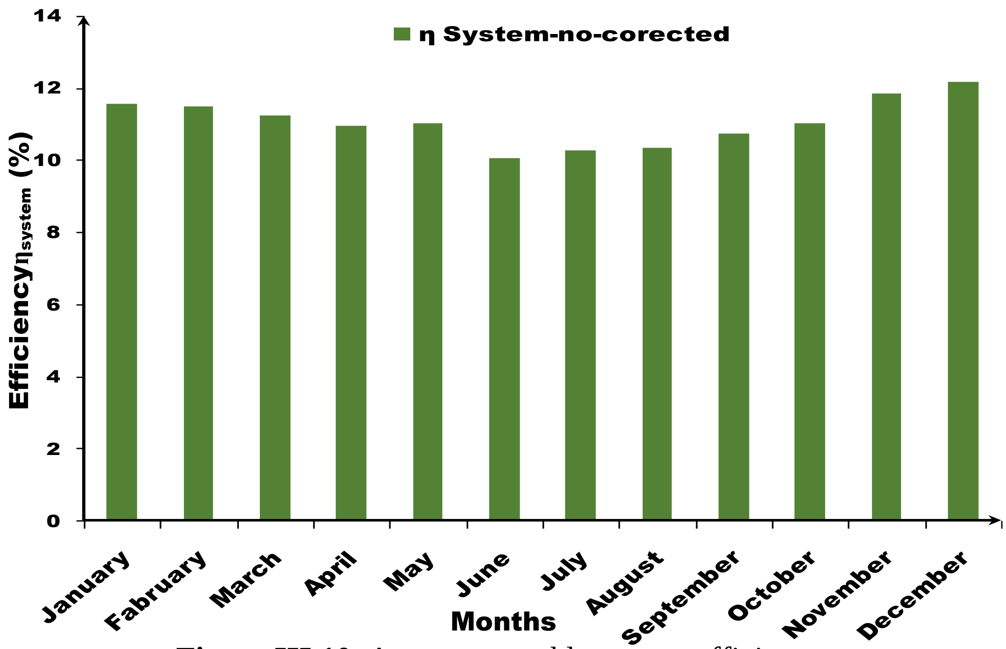

Figure III.10. Average monthly system efficiency.

III.3.2.5. System and capture losses

The monthly average system losses (L_s) and the capture losses (L_c) are presented in Figure III.11.

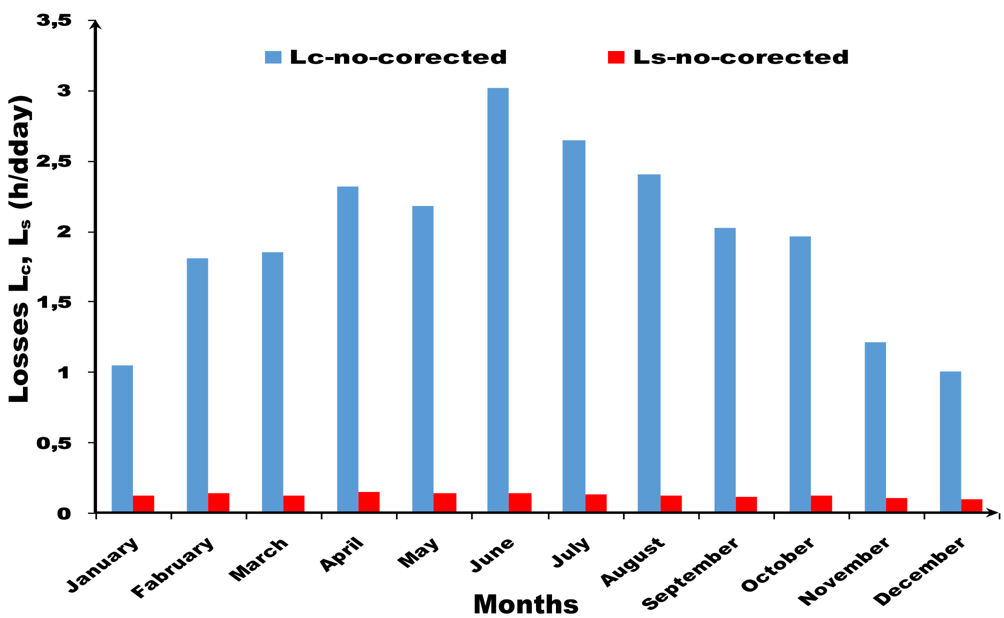

Figure III.11. Average monthly capture losses, and system losses.

The system losses, L_s, vary throughout the year between 0.0953 h/day and 0.1440 h/day. Overall, L_s has a seasonal minimum average equal to 0.095 h/day in winter, whereas the maximum average is in spring at 0.14 h/day.

On the other hand, the highest monthly average L_c is reported in June because of the elevated temperature of the cell, and it increases as the cell's temperature increases. However, it was found that the maximum seasonal average of L_c recorded in June is 3.01 h/day.

III.4. Tilt Radiation Data Correction Methodology

The accuracy of tilt radiation data is critical to evaluate the performance of photovoltaic systems (PV), as it directly influences the main metrics, such as reference performance (Y_r), Performance Rate (P_R) and Final Review (Y_f). In the case of the Ain El-Melh 20 MW_P photovoltaic plant, the preliminary photovoltaic analysis of the 2019 data set revealed inconsistencies in solar irradiance measurements in the plane (G_m), probably due to the misalignment of the pyranometer. This section presents a methodology to identify and correct these discrepancies, ensuring a reliable performance analysis for the plant in 2019.[4]

III.4.1. Identification of Sensor Misalignment

The PV Ain El-Melh plant employs a CR1000X monitoring device to capture global irradiance on the plane, with pyranometer installed at a south-facing 33° slope, corresponding to the orientation of the PV modules.

During the 2019 data review course, the anomalies were identified in slope radiation data, with a particular focus on periods of high solar sunshine.

For example, the measured irradiance on certain days in the 3rd June 2019 was significantly lower than expected, despite the clear conditions of the sky and high environmental temperatures as we see in the figure III.12. The observed discrepancies indicated the possibility of misalignment of pyranometer, which can be attributed to inadequate installation, deviations from the angle of slope or dirt effects.

To confirm the presence of misalignment, registered inclined irradiance (G_m)was compared to the global horizontal irradiance data (GHI) of the same period, adjusted using a transposition model (eg, the Perez model) to estimate the expected irradiance on the plane.

The comparison revealed a consistent underestimation of G_m, with deviations ranging from 5% to 15% on high insolation days. In addition, the cross out of the DC (E_{DC})) power output of the PV subfields showed that the measured G_m did not aligned proportionally with the generated energy, indicating even more a measurement error.

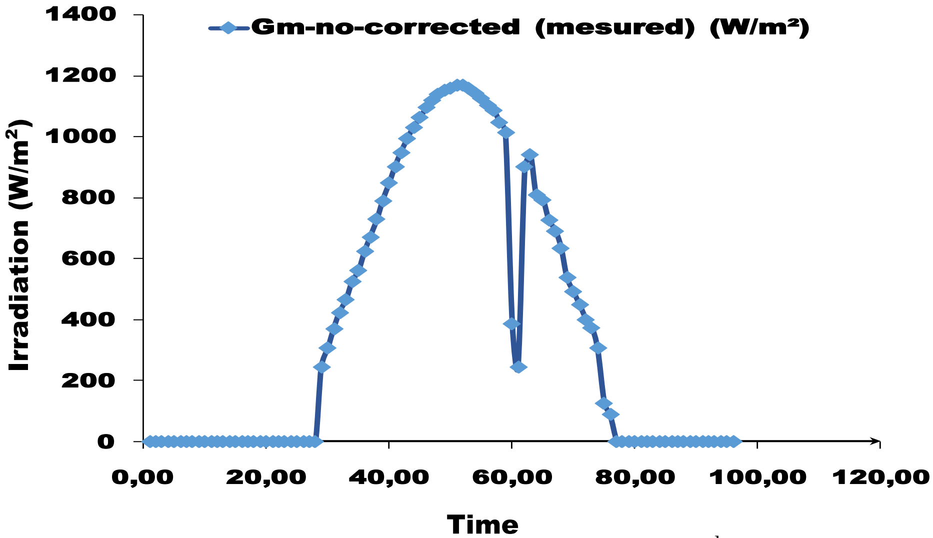

Figure III.12. The measured irradiance on the 3rd June 2019.

III.4.2. Correction Process

To address the missing data issue, a correction method was developed based on the slope radiation data scale using synchronized electrical output measurements[42]. This electric output serves as a proxy for real sun exposure received by the system. The improvement process comprises various stages:

- **Data Synchronization:** Alignment of Tilt Radiation (G_m), Direct Current Energy Output (I_{dc}) and Monitoring Systems Data such as CR1000X and NARI SJ-30 throughout the 2019 data set to ensure temporal consistency.
- **Development of the reference model:** Under ideal conditions such as low temperatures of the module- and clean surfaces of the module, a fundamental relationship between G_m and I_{dc} was established.

This was achieved by selecting the highest quality data from April 2019, during which cleaning operations minimized curse and pyranometer errors, ensuring that the data closely reflect the expected values. Scale I_{DC} using min-max normalization to a range of 0 to 1:

$$I_{dc,scaled} = \frac{I_{dc} - I_{dc,\min}}{I_{dc,\max} - I_{dc,\min}} \quad \text{(III.1)}$$

Where:

$I_{dc,min}$ and $I_{dc,max}$ are the daily minimum and maximum current values, respectively.

- **Adjustment of Tilt Radiation:** The objective of this method is to adjust the tilted irradiance data based on variations in the measured current[42]. It is assumed that the intensity of the tilted irradiance is related to the current's evolution. By applying a correction method that accounts for this relationship, we adjust the irradiance data to better reflect these changes. This adjustment is essential for improving the modeling and prediction of photovoltaic system performance. Once the data is scaled, the correction of tilted irradiance is performed using the normalized current data to adjust the values of Tilt irradiation. The idea is to revert to the original values of G_m, applying an adjustment factor that reflects the variations in I_{dc}.

$$G_{m,corrected} = I_{dc,scaled}\,(G_{m,\max} - G_{m,\min}) + G_{m,\min} \qquad \text{(III.2)}$$

Where:

$G_{m,min}$ and $G_{m,max}$ represent the daily minimum and maximum radiation values.

In this work, we use the Matlab to generate a code can applicate this equation to all the data of every month:

- **Outlier Removal:** Filter out data points affected by non-radiative factors (e.g., inverter failures) by applying statistical thresholds, such as excluding values beyond ±2 standard deviations from the mean.

Note: The quality of correction can be quantitatively assessed using performance metrics such as the residual error between measured and modeled energy outputs.

We use a MATLAB-based methodology to ensure accurate performance analysis, as illustrated in the code provided in the form of a flowchart figure.III.13 summarizing how it works.

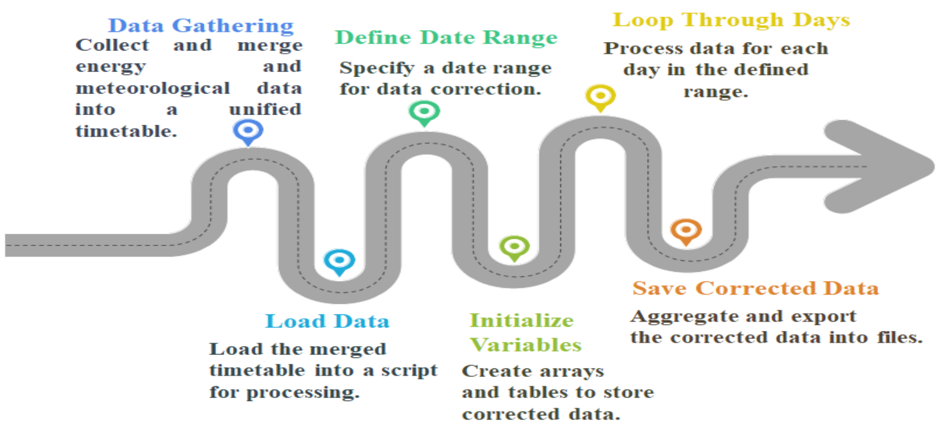

Figure III.13. Flowchart outlining the steps of the data correction process in MATLAB.

III.4.3. Validation of corrected data

The corrected tilt radiation data was validated by comparing the corrected tilt radiation data through the recalculated reference yield ($Y_{r\text{-}corr}$) with actual energy outputs like E_{dc} and E_{ac} provides a direct measure of how well the correction reflects real system performance.

Also cross-referencing with meteorological data which validating the corrected irradiance data against nearby weather station measurements or models like the Perez model helps ensure the irradiance adjustments are physically reasonable and consistent with atmospheric conditions.

The validation process yielded the following results:

III.4.3.1. Meteorological data Comparison

As demonstrated in Figure III.14, the correction methodology appears to be effective in enhancing the accuracy of tilt radiation data. The corrected values offer a more accurate reflection of the true solar irradiance received by the PV plant, effectively validating the use of synchronized DC current data and enhancing the reliability of the meteorological dataset for performance evaluations in 2019.

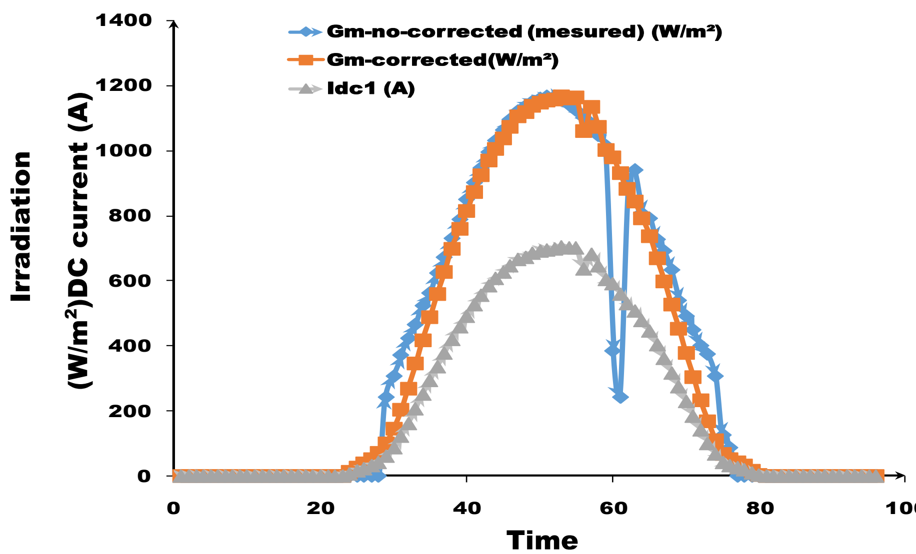

Figure III.14. Measured and corrected tilt irradiation, measured DC current.

III.4.3.2. Performance Metrics

❖ **Reference yields, PV field efficiency and final yield:** If you look to the figureIII.15, you can remark that the reference yield measured is lower than the corrected one due to wrong pyranometer measurement.

The PV field efficiency is the same in both cases while in the final yield there is a small variation.

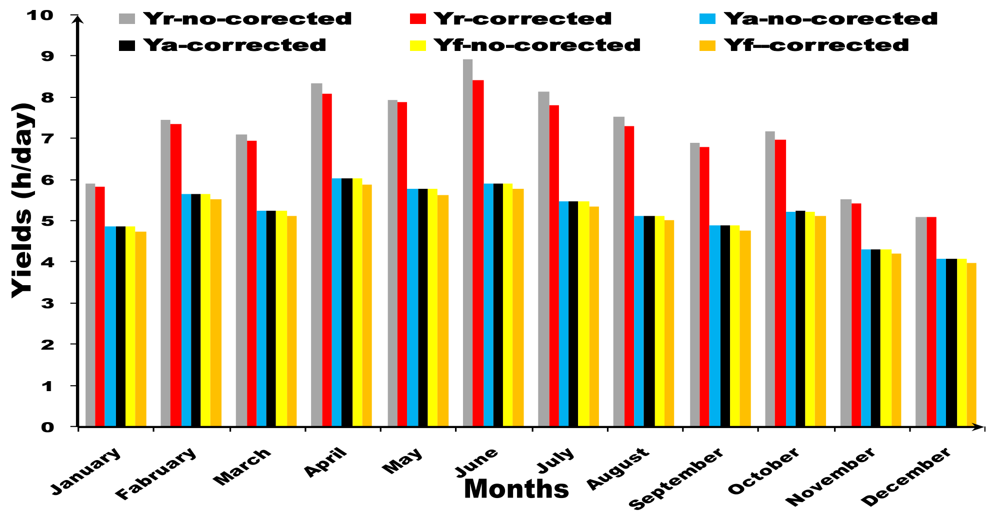

Figure III.15. Monthly evolution of the performance ratio corrected and no corrected.

❖ **Performance ratio:** If you look at Figure 16, you will see a comparison of the performance ratio with the correction method and normal case provides us with valuable insights. It appears that the correction method may have a positive effect on the performance ratio. The monthly changes in the corrected performance ratio (P_R) for 2019 were relatively more stable, ranging from 68.58% in August to 81.54% in January.

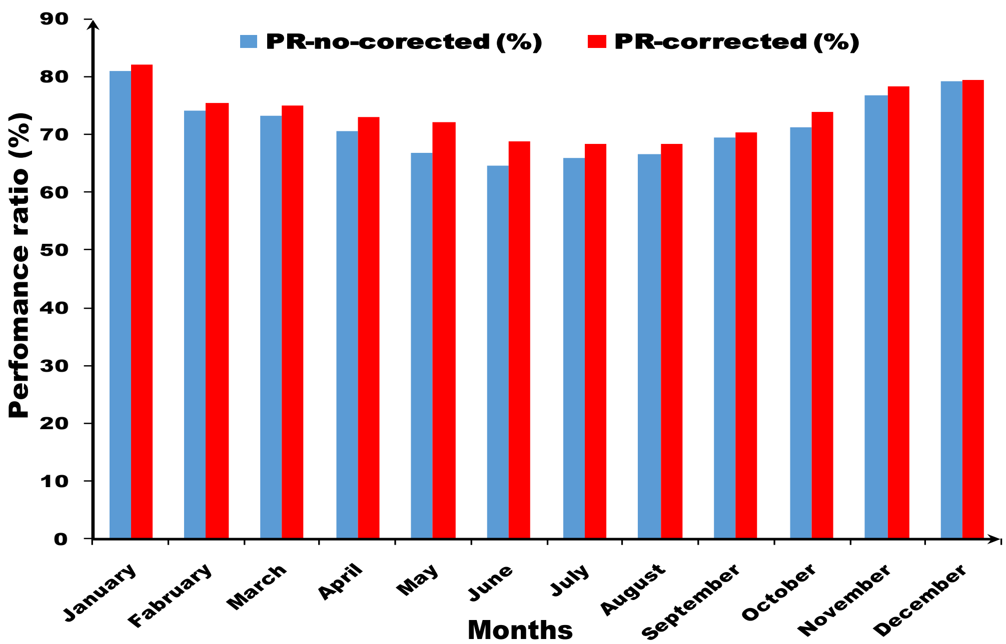

Figure III.16. Monthly evolution of the performance ratio corrected and no corrected.

❖ **Efficiencies:** As illustrated in Figure 17, a comparison of the inverter efficiencies reveals no significant disparities between versions "equal in almost all months".

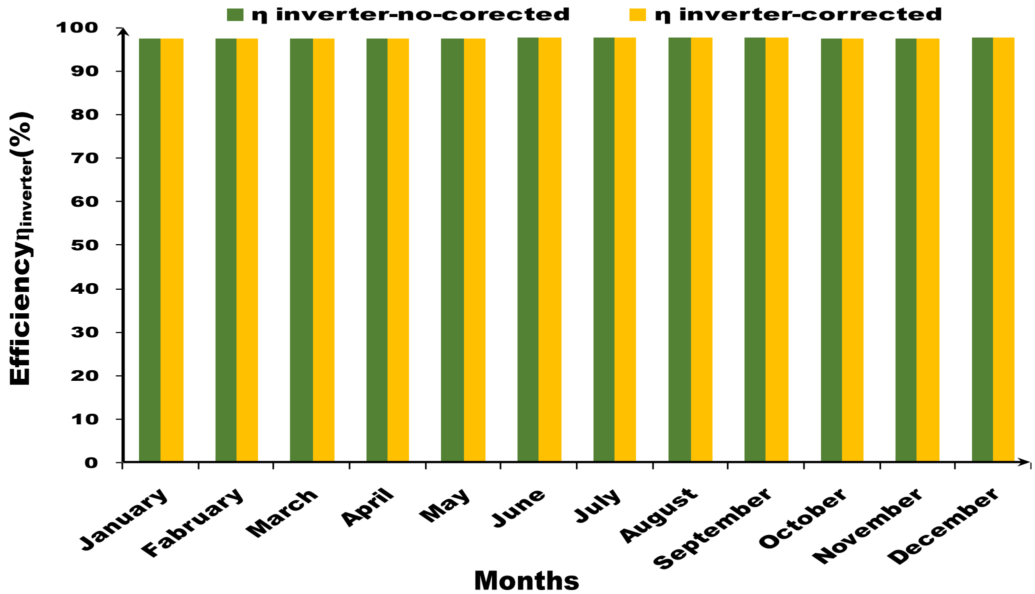

Figure III.17. Monthly evolution of the inverter efficiency corrected and no corrected.

A comparison of the array efficiencies reveals no significant disparities between versions; however, it is observed that the corrected version exhibits a 27.03% increase in efficiency in February(Figure III.18).

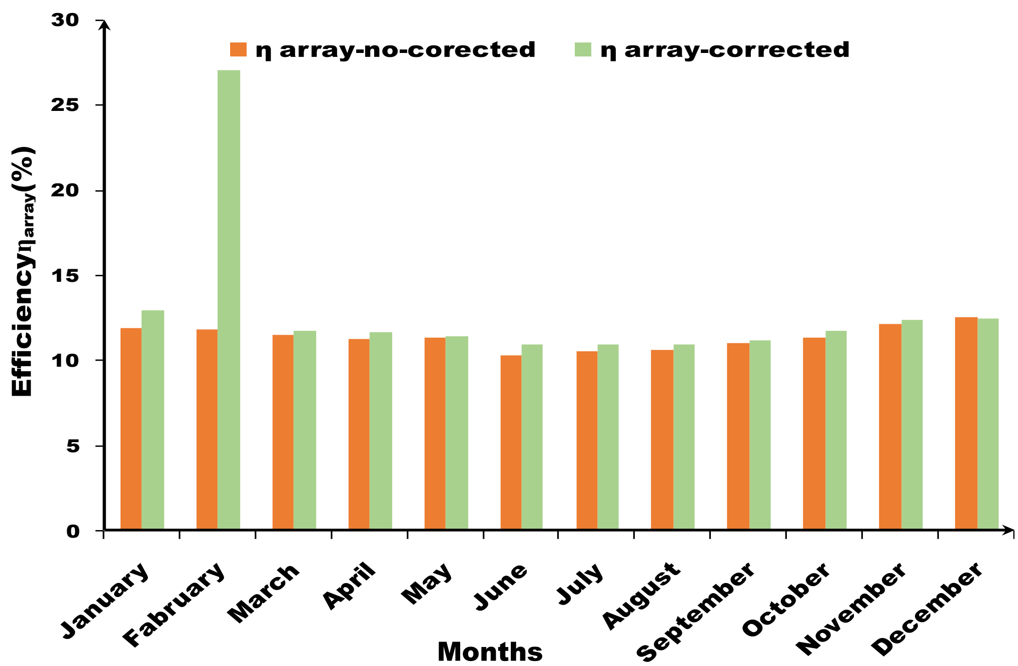

Figure III.18. Monthly evolution of the array efficiency corrected and no corrected.

The figure.19present that the system's maximum efficiency is attained in the corrected case, with 26.38% recorded in the winter "February" period.

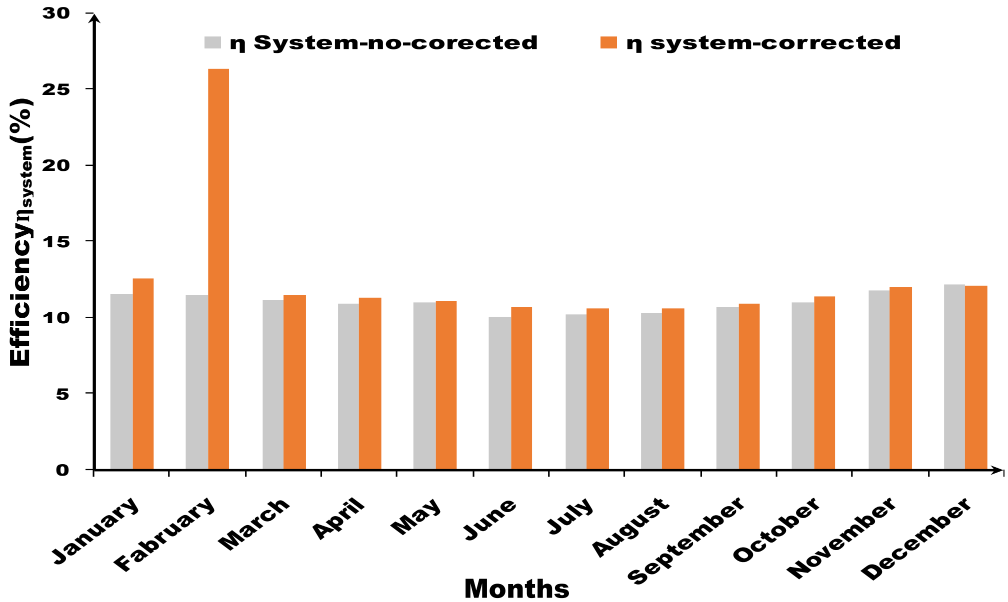

Figure III.19. Monthly evolution of the system efficiency corrected and no corrected.

❖ **System and capture Losses:** A comparison of the losses with the correction method and the standard case is provided, offering valuable insights.

It has been found that the capture losses are reduced in the corrected method especially in the month of February. On other hand, the system losses are the same in both. The figure.20 demonstrated this comparison.

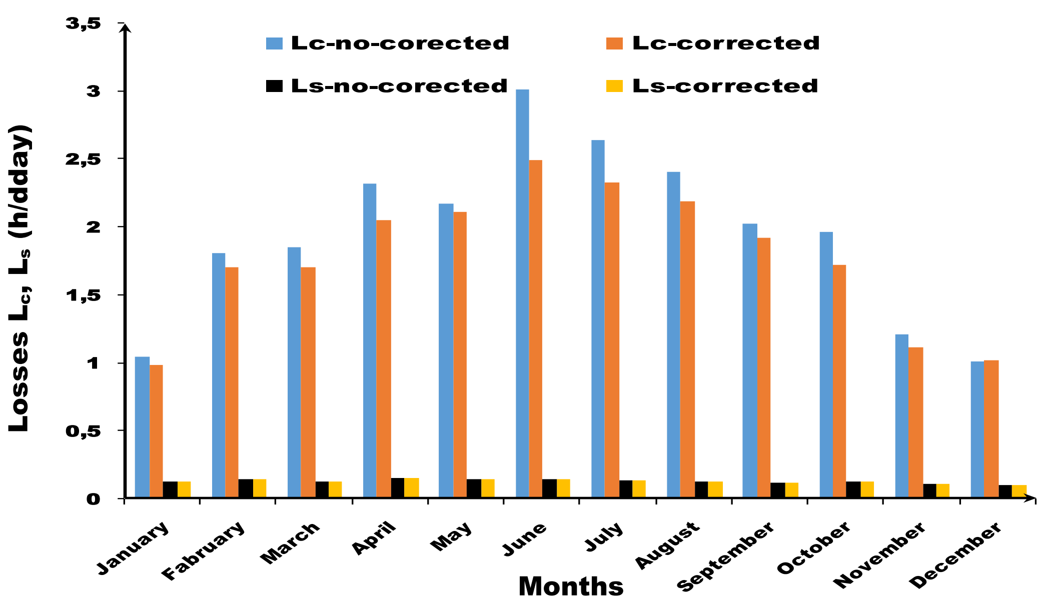

Figure III.20. Monthly evolution of the Losses corrected and no corrected.

III.4.3.3. Discussion

The performance of the Ain El-Melh 20 MWp PV plant was analyzed in 2019 using corrected tilt radiation data.

This analysis revealed a significant enhancement in the accuracy of key metrics, with the performance ratio (P_R) ranging from 68.58% in August to 82.31% in January. The uncorrected range was found to be from 64.8% to 81.19%.

This enhancement highlights the efficacy of utilizing synchronized direct current (DC) current data to address the misalignment of pyranometers, particularly in determining the operational efficiency of the plant under the arid, plateau climate of Algeria.

For instance, the corrected PV plant efficiency (PVE) of 82.31% in January aligns closely with industry standards for well-performing PV plants, typically between 75% and 85%, suggesting that the plant operates near its potential during cooler months.

However, the corrected array efficiency, which peaked at 27.03% in January and exceeded the nominal module efficiency of 15%, raises questions about possible overestimations in the correction process, potentially due to unaccounted low-temperature effects on module performance.

This limitation indicates a necessity for further refinement, such as the incorporation of temperature coefficients into the correction algorithm. However, the plant demonstrated its capacity to function effectively in cooler conditions, as evidenced by the corrected system efficiency of 26.38% in January.

This finding provides practical insights for the optimization of maintenance procedures, such as the increased frequency of cleaning during the summer months, when levels of soiling are typically higher, to mitigate capture losses (e.g., 3.01 h/day in June).

These findings not only validate the correction methodology, but also provide a scalable framework for enhancing performance evaluations in similar large-scale PV plants.

This methodology not only addresses the specific challenges found in Ain El-Melh, but also offers a scalable approach to correcting inclined irradiance data on other large-scale photovoltaic plants that operate under similar altitude and climatically challenging conditions.

III.5. Conclusion

The tilt radiation data corrected method has been shown to enhance the accuracy of the 2019 performance analysis of the Ain El-Melh PV plant. The employment of the direct current (DC) current-based approach, with the correction of the pyranometers deficiency, ensured that the performance matrix accurately reflected the operational efficiency.

This scalable solution not only resolved site-specific data issues, but also provided a framework for enhancing performance evaluation in equal mass PV installations, particularly under challenging environmental conditions.

It is anticipated that future promotion may encompass the implementation of real-time improvement algorithms, with the objective of facilitating the continuity of monitoring processes.

"General Conclusion"

General Conclusion

This thesis has a detailed assessment of operational performance and photovoltaic plant efficiency (PV) connected to 20 MWP of Ain-Melh in M'sila, Algeria, located in a high plateau climate. A highlight of this study is the use of a tilt correction method, which has significantly improved the accuracy of performance evaluations. By refining the calculations of key metrics such as energy yield and performance ratio, which ranged from 68.58% to 82.31% in 2019. This method yielded more profound insights into the substantial solar irradiance levels present within the region, thereby facilitating a more comprehensive understanding of its impact on electrical energy generation. It is also effectively responsible for temperature fluctuations, especially in colder months, such as January, while distinguishing environmental factors such as shading and dirt from the intrinsic performance of the system. This enhanced accuracy has strengthened the reliability of the results and supported a more robust assessment of operational reliability and maintenance strategies. The photovoltaic plant demonstrated a robust energy income and acceptable performance rate, reflecting an efficient solar energy conversion. High levels of solar irradiance in the region significantly increased production, although challenges such as dust and dirt accumulation have been identified as factors that reduce production, emphasizing the need for regular cleaning and maintenance. The effects of the temperature were remarkable- high daytime temperatures reduced the efficiency of photovoltaic cells, but the nighttime's nighttime cooling mitigated some losses. The high reliability of the plant, with the minimum of inactivity time, further highlights the success of routine maintenance and solving quick problems. In addition to the technical achievements, the study lit up the broader impacts of the plant. Economically offers an economic alternative to conventional energy.

❖ **Key Findings**

- Energy Yield and Performance Ratio (PR)

The PV plant in Ain El-Melh demonstrated a robust energy yield, the performance ratio, a key indicator of PV system efficiency, was found to be within acceptable ranges, suggesting effective conversion of solar irradiance into electrical energy.

- Impact of Temperature

Moderate temperatures, particularly in January, had a noticeable effect on the performance of the PV modules. Elevated temperatures can reduce the efficiency of PV cells, leading to decreased energy output.

However, the cooling effect of the high plateau's nighttime temperatures somewhat mitigated this issue.

- Irradiance Levels

The high plateau region benefits from high levels of solar irradiance, which positively affects the overall energy production of the PV plant. The abundance of sunlight is a significant advantage for solar power generation in Ain El-Melh.

- Dust and Soiling

Dust accumulation reduced output, emphasizing the need for consistent cleaning and maintenance.

- System Reliability and Maintenance

The PV plant exhibited high reliability with minimal downtime. Routine maintenance and prompt addressing of any technical issues were critical to sustaining the plant's performance.

- Economic and Environmental Impact

The large-scale PV plant contributes to the reduction of greenhouse gas emissions and dependence on fossil fuels, aligning with environmental sustainability goals. Economically, the plant provides a cost-effective alternative to conventional energy sources, particularly in remote areas.

- **Further Research**

Future studies could refine the tilt correction method and explore its broader application. At a similar time, research could investigate long-term climatic effects on PV systems to enhance durability and performance in analogous environments.

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