Université Constantine 1 - Frères Mentouri
Faculté des Sciences de la Technologie
Département d'Électrotechnique

N° de Série : 81/D3C/2024
N° d'ordre : 05/eltech/2024

Production d'énergie électrique par sources solaires Photovoltaïques : dans le Sahara d'Algérie

THÈSE

Présentée pour l'Obtention du Diplôme de

Doctorat de Troisième Cycle

Par

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Soutenue publiquement
Le: 28 /11 /2024

University of Constantine 1 – Mentouri Brothers
Faculty of Sciences and Technology
Department of Electrotechnical

Serial N° : 81/D3C/2024
Order N°: 05/eltech/2024

Production of electrical energy by photovoltaic solar sources: in the Sahara of Algeria

THESIS

Presented to obtain
the Doctorate diploma in the Third Cycle LMD

By

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Publicly supported
On : 28 /11/2024

الجمهورية الديمقراطية الشعبية الجزائرية
وزارة التعليم العالي والبحث العلمي
جامعة الإخوة منتوري – قسنطينة

الرقم التسلسلي: 81/D3C/2024
رقم الأمر: 05/eltech/2024

أُطرُوحَة
للحصول على درجة الدكتوراه الدورة الثالثة ل م د في الهندسة الكهربائية

تخصص: شبكات كهربائية

المقدمة من طرف:

يونــس محــمد

ماستر في الشبكات الكهربائية

العنوان

إنتـاج الطـاقـة الـكهربـائـية بـإستخـدام أنـظمة الطاقــة الشـمسية : في صـحـراء الـجزائـر

Soutenue le : 28\ 11\ 2024

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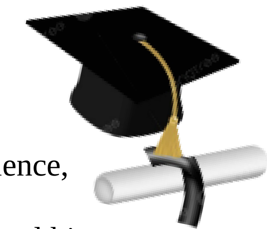
ACKNOWLEDGEMENTS



This dedication is surrounded by our deepest emotions

I would like to thank my supervisor, **Pr. Djamel LABED**, for his guidance, experience, and invaluable advice through the work on both the master's and the Ph.D. thesis and his support of the content of the work.

My sincere and deepest appreciation is extended to my esteemed co-supervisor **Pr. Nabil KAHOUL** for his consistent support and guidance during the running of this thesis, his support, encouragement, and disponibility. And special thanks to **Pr. Hocine CHEGHIB** who provides us considerable support in completing this work in optimal conditions, without forgetting **Pr. Saleh SAAD**, **Farouk LAOUAR**, and the entire Laboratory team of Systèmes Electromécaniques LSELM, University of Badji Mokhtar Annaba.

Also, our thanks extend to the Research Unit of Renewable Energy in the Saharan Middle of Algeria **(URERMS)**, and the **SKTM** team at Zaouiet Kounta, particularly **Pr.Ammar Neçaibia,** for their kind availability and the opportunity they offered me to access the data and use the necessary types of equipment. My deepest gratitude to the jury members for their invaluable contributions to the evaluation of my thesis.

My thanks also extend to my doctoral colleagues, with a special mention to **Belhadj CHEKAL AFFARI** and **Zoubida KHERICI** for their collaboration, their valuable help, and the friendly moments shared throughout the doctoral career.

My biggest thanks go to my family for all the support you have shown me through this research, to my ***Mother*** for her patience and encouragement, as well as to my great ***Father***.

And finally, we express our sincere respect to all those who participated directly or indirectly in the success of our study.

YOUNES Mohammed

Production of electrical energy by photovoltaic solar sources: in the Sahara of Algeria

List of Contents

LIST OF FIGURES........10
LIST OF TABLE........12
LIST OF ACRONYMS AND ABBREVIATIONS........13
ملخص........15
Résumé........16
ABSTRACT........17
PROBLEM STATEMENT........18
GENERAL INTRODUCTION........19
THESIS OUTLINE........22
CHAPTER I: ***Solar energy production in Algeria: Status and perspectives***........23
1.1 Introduction........24
1.2 State of global renewable energy........25
1.3 Global Solar Photovoltaic Energy........26
1.4 Status of renewable energy: framework of Algeria........27
1.5 Renewable Energy in Algeria: Strategies and targets by 2030........28
1.6 Potential, Evolution and Perspectives of solar energy in Algeria........29
1.7 Solar capacity installed for National Program for Renewable Energy........31
1.8 Status of PV industry in the Algerian market........32
1.9 Legislative and institutional structures for the energy transition........33
1.10 Conclusion........35
CHAPTER II: ***Solar Photovoltaic System and Applications***........36
2.1 Introductions........37
2.2 Photovoltaic systems........38
2.2.1 Off-grid systems (stand-alone)........38

2.2.2 Grid-connected systems 39

2.3 Components of Photovoltaic (PV) Systems 40

2.3.1 PV Cells, Modules, Strings, and Arrays 40

- PV Cells 40
- PV module: specification, Standards, and Certifications 40

Standard Test Conditions (STC) 41

Nominal Operating Temperature (NOCT) 42

- String of PV modules 43
- Photovoltaic PV Array 44

2.3.2 Inverters DC - AC 46

- Essential factors to consider for selecting the size of power inverter 49

2.3.3 Batteries 49

- Types of batteries 50

2.4 Performance evaluation of PV systems 50

2.4.1 Energies yields 51

- Energy production by the PV system (E_{dc}) 51
- The AC energy generated and delivered (E_{ac}) 51
- Reference yield (Y_r) 51
- Array yield (Y_A) 51
- Final yield (Y_f) 52

2.6.1 Energies efficiencies 52

- PV panel efficiency (η_{PV}) 52
- Inverter efficiency (η_{inv}) 52
- System efficiency (η_{Sys}) 52
- Performance ratio (PR) 53
- Capacity factor (CF) 53

2.6.1 Energies losses 53

- Array capture loss (LC) 54
- System loss (LS) 54

2.7 Factors and considerations for sustainable Photovoltaic Power Plant investment 54

- Location 54
- Climate 55
- Political 55

2.6 Conclusion 55

CHAPTER III: ***Performance study of photovoltaic panels in Algeria Desert*** 56

3.1 Introduction: 57
3.2 Overview of the region 58
3.3 Experimental study 58
3.4 Review of Solar radiations influencing the PV panel performance 59

- Performance evaluation and degradation modes 62

3.5 Review of temperature influencing the PV panel performance 66
3.5.1 Ambient temperature 66
3.5.2 Impact of high ambient temperature accompanied by solar irradiation 69
3.6 Review on dust accumulation influencing PV panel performance 75
3.6.1 Impact of dust deposition on the surface of PV modules 75
3.7 Conclusion 79

CHAPTER IV: ***Monitoring, and performance analysis of 6MW grid-connected in desert: Case study*** 80

4.1 Introduction 81
4.2 Description of location study 81
4.3 Description of the 6 MW photovoltaic power plant 82
4.4 Components and characteristics of the Zaouiet Kounta PV plant 83
4.4.1 Photovoltaic PV panel 83
4.4.2 Connections box 85
4.4.2.1 Junction boxes 85
4.4.2.2 Parallel Box 86
4.4.2.3 General Box 87
4.4.2.4 Inverter 89

4.4.2. Transformer 90
4.4.3 Weather station 91
4.4.4 Monitoring and control system 92
4.5 Environmental factors affecting the performance of PV power plants in desert 93
4.5.1 Monitoring of climatic data in Desert region 93
4.5.1.1 Monitoring of solar irradiation 94
4.5.1.2 Monitoring of ambient temperature 95
4.5.1.3 Monitoring of wind speed, humidity, and atmospheric pressure 97
4.5 Study of the effect of ambient temperature accompanied by solar irradiation on system's performance 98
4.6 Conclusion 102
GENERAL CONCLUSION 103
BIBLIOGRAPHY 106

LIST OF FIGURES

Fig.1.1	Global Renewable Energies Generation in 2022
Fig.1.2	Global solar power generation in 2022
Fig.1.3	Installed capacity of renewable energies from 2014 to 2019
Fig.1.4	National park evolution for electrical production
Fig.1.5	Map of global horizontal irradiation of Algeria
Fig.1.6	Solar power capacity in Algeria from 2012 to 2022 in Mw
Fig. 2.1	Diagram of solar Photovoltaic system
Fig 2.2	An off-grid solar photovoltaic (PV) system
Fig 2.3	A grid-connected solar photovoltaic (PV)
Fig. 2.4	PV module components
Fig. 2.5	Different String connections with identical and non-identical PV modules
Fig. 2.6	Cases of PV Arrays with identical and non-identical strings
Fig 2.7	PV cell, module, string and PV array
Fig. 2.8	Solar inverter conversion process DC into AC
Fig.2.9	Electrical and mechanical specifications, operating conditions of solar inverter
Fig 3.1	The experimental study at URER-MS
Fig.3.2	Global Solar irradiation in year
Fig.3.3	Daily solar irradiation for: **(a)** October 2017, **(b)** January 2018, **(c)** April 2018, **(d)** July 2018
Fig. 3.4	Solar irradiation effect: Solmetric PV Analyzer Characterization of polycrystalline PV module
Fig. 3.5	Solar irradiation effect: Solmetric PV Analyzer Characterization of monocrystalline PV module
Fig. 3.6	Bus bar yellowing of polycrystalline PV module
Fig. 3.7	EVA Browning discoloration of monocrystalline PV module
Fig.3.8	Effect of module temperature

Fig.3.9	Annual ambient temperature
Fig.3.10	Ambient temperature: (a) October, (b) January, (c) April, (d) July
Fig.3.11	Module's temperature of tested panels
Fig.3.12	Module's temperature effects: Solmetric PV Analyzer characterization for Polycrystalline PV module
Fig.3.13	Module's temperature effects: Solmetric PV Analyzer characterization for monocrystalline PV module
Fig.3.14	Fingers and bus bars discoloration of polycrystalline PV module
Fig.3.15	EVA Browning / dark browning discoloration of monocrystalline PV module
Fig.3.16	Dust deposition effect: Solmetric PV Analyzer characterization for polycrystalline PV module
Fig.3.17	Dust deposition effect: Solmetric PV Analyzer characterization for monocrystalline PV module
Fig.3.18	Dust deposition on tested polycrystalline PV module
Fig.3.19	Dust deposition on tested monocrystalline PV module
Fig. 4.1	Zaouiet Kounta 6MW PV power plant
Fig. 4.2	Zaouiet Kounta 6MW PV power plant Schematic diagram
Fig 4.3	YINGLI SOLAR PV panel specification
Fig. 4.4	Junction box
Fig. 4.5	Parallel box
Fig. 4.6	Connection diagram of parallel box
Fig.4.7	General Box
Fig. 4.8	Connection diagram of general box
Fig.4.9	SUNGROW Inverter (Shelter)
Fig. 4.10	SUNTEN transformator
Fig 4.11	NARI weather station equipment
Fig 4.12	NARI weather station at Zaouiet Kounta PV station
Fig 4.13	Principle control interface (SCADA)
Fig 4.14	Five years monitoring of solar irradiation

Fig 4.15 Five years monitoring of ambient temperature

Fig 4.16 Linear fitting of solar irradiation against generated power

Fig 4.17 Effect of ambient temperature on the generated power

Fig 4.18 Energy yield performance for the monitored period during summer seasons

Fig 4.19 Performance Ratio for the monitored period during summer seasons

LIST OF TABLE

Tab.1.1 Renewable energy program and targets by 2030

Tab.1.2 Solar Potential in Algeria

Tab.1.3 Installed solar generation stations in Algeria

Tab.1.4 Solar module factories in Algeria

Tab 2.1 Solar inverter types

Tab 3.1 Electrical parameters and degradation rates of tested polycrystalline PV module

Tab 3.2 Electrical parameters and degradation rates of tested monocrystalline PV module

Tab 3.3 Effect of module's temperature on the electrical parameters of tested polycrystalline PV module

Tab 3.4 Effect of module's temperature on the electrical parameters of tested monocrystalline PV module

Tab 3.5 Effect of dust deposition on the electrical parameters of tested polycrystalline PV module

Tab 3.6 Effect of dust deposition on the electrical parameters of tested polycrystalline PV module

Tab 4.1 Photovoltaic module specifications at standard test conditions STC (1000 W/m² and 25°C)

Tab 4.2 Technical characteristics of SUNGROW junction box

Tab 4.3 Technical characteristics of SUNGROW parallel box

Tab 4.4 Technical characteristics of SUNGROW general box

Tab 4.5 Technical characteristics of SUNGROW Inverter (Shelter)

LIST OF ACRONYMS AND ABBREVIATIONS

RE	Renewable Energy
PV	Photovoltaic
IRENA	**I**nternational **R**enewable **E**nergy **A**gency
PNEREE	**N**ational **P**rogram of **R**enewable **E**nergies and **E**nergy **E**fficiency
MEM	**M**inistry of **E**nergy and **M**ines
MERE	**M**inistry of **E**nvironment and **R**enewable **E**nergy
CEREFE	**C**ommission for **R**enewable **E**nergies and **E**nergy **E**fficiency
CREG	**C**ommission for **E**nergy and **G**as **R**egulation **A**lgeria
CDER	**R**enewable **E**nergy **D**evelopment **C**enter
URERMS	**R**esearch **U**nit for **R**enewable **E**nergies in **S**aharan **R**egion
URAER	**A**pplied **R**esearch **U**nit for **R**enewable **E**nergies
UDES	**S**olar **E**quipments **D**evelopment **U**nit
SKTM	**S**hariket **K**ahraba wa **T**aket **M**outadjadida
IEC	**I**nternational **E**lectrotechnical **C**ommission
STC	**S**tandard **T**est **C**onditions
NOCT	**N**ominal **O**perating **T**emperature
EVA	**E**thylene-**V**inyl **A**cetate
Bwh	Hot desert climate (Köppen-Geiger system class)
SCADA	**S**upervisory **C**ontrol and **D**ata **A**cquisition
Hz	Frequency in **H**ertz
GW	**G**ega-**W**att
MW	**M**ega-**W**att
kW	**k**ilo **W**att
kWh	**k**ilo **W**att **h**ours
DC	**D**irect **C**urrent
AC	**A**lternating **C**urrent

IP **I**ndex of **P**rotection

E_{DC} **D**irect **E**nergy **G**enerated and **D**elivered

E_{AC} **A**lternating **E**nergy **G**enerated and **D**elivered

Y_r **R**eference yield

H_t Solar radiation arriving at the surface

G_{STC} **R**eference solar radiation

Y_A Array yield

P_{nom} **N**ominal rated power

Y_f Final yield

η_{PV} PV panel efficiency

η_{inv} Inverter efficiency

η_{Sys} System efficiency

PR **P**erformance **R**atio

CF **C**apacity **F**actor

LC Array capture loss

LS **S**ystem **L**osses

UV **U**ltraviolet rays

c-Si **C**rystalline silicon

Voc Open-circuit voltage

Isc Short-circuit current

V_{mpp} Maximum voltage

I_{mpp} Maximum current

R_{sh} **S**hunt **R**esistance

R_S **S**eries **R**esistance

FF **F**ill **F**actor

ملخص

تعد المناطق الصحراوية هدفًا جذابًا للاستثمار الناجح والمستدام في توليد الكهرباء بالطاقة الشمسية نظرًا لخصائصها الجغرافية النموذجية. حاليا، تعمل الحكومة الجزائرية على تعزيز برامج الطاقة المتجددة، مما يمهد الطريق لمشاريع واسعة النطاق.

ومن ناحية أخرى، تشكل المناخات القاسية أكبر التحديات أمام موثوقية ومتانة وأداء المنشآت الكهروضوئية في البيئات الصحراوية. في الصحراء الجزائرية، تعتبر العديد من العوامل البيئية، مثل الإشعاع الشمسي العالي، ودرجات الحرارة القصوى، من عوامل الضغط التي لا يمكن تجنبها.

يهدف العمل إلى فهم التحديات التي تواجه أداء وتشغيل النظام الكهروضوئي في المناخات القاسية وتقديم مجموعة محددة من الإجابات على الأسئلة التي يجب معالجتها لفهم التحديات المتعلقة بموثوقية التقنيات الكهروضوئية على المدى الطويل وتحسين التشغيل والإنتاج الاقتصادي لأنظمة الطاقة الكهروضوئية. وفي هذا السياق، أجريت دراسة في وحدة أبحاث الطاقة المتجددة في المنطقة الصحراوية بالجزائر (URERMS) لتحليل الأداء والموثوقية طويلة المدى للوحدات الكهروضوئية العاملة في الظروف المناخية الصحراوية الحارة والتعرف على أنماط التدهور المنسوبة إلى هذه المناخات. وذلك من خلال إنشاء قاعدة بيانات تمكن من تقييم أداء النظام على المدى الطويل.

بالإضافة إلى ذلك، على نطاق واسع ومن أجل تقييم طويل المدى للأنظمة الكهروضوئية واسعة النطاق المثبتة في المناطق الصحراوية، تم إجراء دراسة أخرى في محطة الطاقة الكهروضوئية بزاوية كونتا بقدرة 6 ميجاوات في أدرار، الجزائر، على مدى خمس سنوات متتالية. فترة المراقبة، التي تشمل جمع بيانات الطقس وتشغيل المحطة الكهروضوئية، لتحليل تأثير الإشعاع الشمسي ودرجة الحرارة المحيطة والظروف الأخرى على الأداء طويل المدى لمحطة الطاقة الكهروضوئية وتقديم توصيات بشأن التحسينات المستقبلية المحتملة في الكفاءة و التوسع في استخدام الطاقة النظيفة في المناطق الصحراوية.

الكلمات المفتاحية: صحراء الجزائر؛ توليد الكهرباء بالطاقة الشمسية؛ مناخات قاسية؛ تحليل الأداء؛ مصداقية.

Résumé

Les régions désertiques constituent une cible attrayante pour un investissement réussi et durable dans la production d’électricité solaire en raison de leur profil géographique typique. Actuellement, le gouvernement algérien promeut des programmes d’énergies renouvelables, ouvrant la voie à des projets à grande échelle.

D’un autre côté, les climats rigoureux posent les plus grands défis en termes de fiabilité, de durabilité et de performances des installations photovoltaïques dans les environnements désertiques. Dans le désert algérien, plusieurs facteurs environnementaux, tels qu’un fort rayonnement solaire et des températures extrêmes, sont considérés comme des facteurs de stress inévitables.

Le travail vise à comprendre les défis liés à la performance et au fonctionnement du système photovoltaïque dans des climats rigoureux et à fournir un ensemble concret de réponses aux questions qui doivent être abordées pour comprendre les défis liés à la fiabilité à long terme des technologies photovoltaïques et pour améliorer la fonctionnement et rendement économique des systèmes d’énergie photovoltaïque. Dans ce contexte, une étude a été menée à l'unité de recherche sur les énergies renouvelables de la région saharienne de l'Algérie (URERMS) pour analyser les performances et la fiabilité à long terme des modules photovoltaïques exploités dans des conditions climatiques désertiques chaudes et reconnaître les modes de dégradation attribués à ces climats. , en établissant une base de données qui permettra d'évaluer les performances du système à long terme.

Par ailleurs, à grande échelle et pour l'évaluation à long terme des systèmes photovoltaïques à grande échelle installés dans les régions désertiques, une autre étude a été réalisée à la centrale photovoltaïque de Zaouiet Kounta de 6 MW à Adrar, en Algérie, sur une période de cinq années consécutives. période de surveillance, comprenant la collecte de données météorologiques et le fonctionnement de la station photovoltaïque, pour analyser l'impact de l'irradiation solaire, de la température ambiante et d'autres conditions sur les performances à long terme de la centrale photovoltaïque et pour formuler des recommandations pour de futures améliorations potentielles de l'efficacité et l’expansion des énergies propres dans les régions désertiques.

Mots-clés : désert algérien ; production d'électricité solaire ; climats rigoureux ; analyse de performance ; fiabilité.

ABSTRACT

Desert regions are an appealing target for successful and sustainable investment in solar electricity generation due to their typical geographic profile. Currently, the Algerian government is promoting renewable energy programs, paving the way for large-scale projects.

On the other hand, harsh climates pose the greatest challenges to the reliability, durability, and performance of photovoltaic installations in desert environments. In the Algerian desert, several environmental factors, such as high solar irradiation, and extreme temperatures, are considered unavoidable stressors.

The work aims to understand the challenges to the performance and operation of the PV system in harsh climates and provide a concrete set of answers to the questions that must be addressed to understand challenges related to the long-term reliability of photovoltaic technologies and to improve the operation and economic output of photovoltaic power systems. In this context, a study was conducted at the research unit of renewable energy in the Saharan region of Algeria (URERMS) to analyze the performance and long-term reliability of PV modules operated in hot desert climatic conditions and recognize degradation modes attributed to these climates, by establishing a database that will enable system evaluations of the long-term performance.

In addition, on a large scale and for long-term evaluation of large-scale PV systems installed in desert regions, another study was carried out at the Zaouiet Kounta 6 MW photovoltaic power plant in Adrar, Algeria, over a five-consecutive-year period of monitoring, comprising weather data collection and the PV station's operation, to analyze the impact of solar irradiation, ambient temperature, and other conditions on the long-term performance of the photovoltaic power plant and to make recommendations for potential future improvements in efficiency and the clean energy expansion in desert regions.

Keywords: Algeria’s desert; solar electricity generation; harsh climates; Performance analysis; Reliability.

PROBLEM STATEMENT

In this thesis, the performance of a Photovoltaic power plant in hot climate of the Algerian desert will be investigated and analyzed. This will be accomplished by establishing a database containing information on the technical performance of photovoltaic technologies in Algeria's desert climate and, that will enable the system evaluation of the long-term performance.

One major goal of this thesis is to gain an understanding of the challenges to the performance and operation of the PV system in harsh climates and, to provide a concrete set of answers to the questions that must be addressed to understand challenges related to the long-term reliability of photovoltaic technologies and to improve the operation and economic output of photovoltaic power systems.

The assessment of system performance and operation carried out in this thesis may be of great use to the PV industry to improve the operating lifetime of new PV technology and aid the development of new accelerated laboratory tests.

GENERAL INTRODUCTION

The world is in an energy crisis due to the finite amount of available fossil fuels, which are our main energy source today. Currently, the deployment of Renewable Energy (RE) around the world is increasing sharply, recording remarkable growth rates of RE technologies, particularly solar energy, across regions and nations that are characterized by favorable conditions for capacity production [1], [2].

Solar energy is referred to as renewable or sustainable energy and is found everywhere worldwide, compared to other energy types such as fossil fuels and minerals. In addition, energy generation from photovoltaic is essentially non-polluting; photovoltaic panels do not need water for electricity generation, in contrast to steam plants fired by fossil fuels and nuclear power[1].

By looking at the abundance of solar resources in deserts that are estimated to generate five times the world's annual electricity demand, solar energy is becoming incredibly interesting for countries like Algeria (Sahara Desert), Saudi Arabia (Arabian Desert), Chile (Atacama Desert), USA (Mojave Deserts), and China (Gobi Desert) [3].

Solar photovoltaic (PV) is the world’s fastest growing energy technology. Moreover, the solar PV markets have shown maturity in recent years in terms of PV technology development, efficiencies, and falling prices of PV modules, leading to increased competitiveness with traditional power sources. This uptrend in PV module development is expected to be maintained in the coming years as new markets expand, especially in desert areas that are considered interesting zones for PV applications due to their unique features [2], [4], [5].

Solar PV technology has the adaptability, flexibility, and simplicity to design systems for different regions. Furthermore, the use of PV systems in electricity generation is set up for a wide range of applications, comprising its two main types: standalone (off-grid) and grid-connected (on-grid), which can be applied from single applications to large-scale deployment as solar farms, providing the needed amount of power [6], [7]. The PV system of the grid-connected type can be integrated into existing electricity grids with relative simplicity, while the standalone type can provide enough energy for the appropriate designed applications [8].

Generally, PV module performance significantly contributes to the quality and commercial attractiveness of a PV system, which are primarily determined by its performance in the field, cost, and lifetime.

In desert regions, solar PV modules will be exposed to simultaneous environmental stresses like higher temperatures, solar irradiation, dust, and ultraviolet (UV) irradiation. These factors often lead to a gradual decrease in the overall performance of PV systems, resulting in a big drop in the output power by directly affecting the electrical performance, in terms of short circuit current (Isc), and open circuit voltage (Voc) and promoting several failure and degradation modes, highlighting EVA encapsulant discoloration (yellowing, browning, and dark browning), delamination, corrosion, etc., indicating that the desert presents the most difficult environment which create a serious challenges for PV modules. In fact, the operation under this climate is substantially different in comparison to the information given by tests under Standard Test Conditions (STC) by manufacturers [3], [9]–[11].

According to the European Technology and Innovation Platform report [12], long-term reliability is an important factor in PV systems. The reliability and performance of a PV module are directly related to the local climate. Additionally, long-term reliability and lifetime are aspects to consider for modules that operate under conditions like those found in deserts far from standards.

In conclusion, it is imperative to develop a new PV module technology that will be adequate, suitable, and more challenging for harsh desert conditions by improving reliability, operating lifetime, and efficiency to reduce challenges for PV electricity generation in deserts in terms of the costs of the operation and maintenance of the PV plants, and therefore of the electricity.

THESIS OUTLINE

Chapter one introduces the reader to the delightful world's renewable energy sector, and it focuses on the status of renewable energy in Algeria, particularly solar photovoltaic, by presenting its potential, evolution, perspectives, strategy, and target for the Algerian program for renewable energy by 2030.

The second chapter deals with an overview of solar photovoltaic (PV) systems, their types, and their main components, along with details. This chapter also presents a demonstration of the PV system topology and configurations. Besides that, the performance evaluation of PV systems has been detailed through a specific analysis technique based on the IEC 61724 standard, particularly on large scales, and highlights factors and considerations for the best location to achieve sustainable investment in photovoltaic power plants.

The third chapter presents an in-depth study of environmental factors influencing the performance and reliability of standard PV panels in the desert by choosing the Algerian desert as a case study. The chapter not only provides the challenges related to the optimal performance of PV modules and electricity generation but also discusses the different failure modes and degradation that can appear on these PV panels in this region.

The fourth chapter analyses the impact of climate conditions on the performance of a 6-MW grid-connected PV power plant situated in the southwest of Algeria, Adrar. Besides that, an investigation study was conducted on the impact of solar irradiation and ambient temperature on the PV station's performance over a five-consecutive-year period of monitoring. The main objective of this chapter is to carry out in-depth analyses and look at the PV plant's operation under harsh environmental conditions to make recommendations for potential future improvements in efficiency and the expansion of clean energy in southern Algeria.

CHAPTER I

Solar energy production in Algeria: Status and perspectives

1.1 Introduction

Energy demand has experienced rapid growth over the past decades due to the rapid growth of the population and economy. Many countries that use conventional power generation are heavily dependent on fossil fuels for global electricity generation. However, due to the fluctuation of fuel prices and the need to reduce the environmental impact, there is an increasing effort to move toward renewable energies as an alternative source, contributing to the energy mix to mitigate fossil fuel dependency [13].

Nowadays, many countries have shown interest in renewable energy sources to meet their energy demands. Therefore, significant investments have been made in developing countries towards implementing new policies and programs focused on renewable energy (RE) generation by achieving a higher contribution of RE in the energy mix and energy transitions. Indeed, there has been significant technological progress in the last two decades, particularly in renewable energy sources such as solar photovoltaic and wind power. As a result, the cost of electricity generation through these sources has become comparable to traditional methods of production, which encourages its adoption and deployment on a larger scale [13], [14].

Solar photovoltaic technology has gained significant maturity over several decades. Indeed, it plays a leading role in the current energy transition and energy security. where the newer solar PV technology can provide a host of benefits by achieving the dual goals of addressing environmental concerns and ensuring the efficiency of reliable energy delivery with cost-efficiency [15], [16]. On the other hand, the global PV installed witnessed an increase in cumulative capacity from 483.1 GW in 2018 to 580.2 GW in 2019, indicating a relative increase of approximately 21% (IRENA, 2020) [17], [18].

This chapter is dedicated to presenting the world's renewable energy sector. In addition, it focuses on the status of renewable energy in Algeria, particularly solar photovoltaic, its potential, evolution, and perspectives, taking into account the Algerian program for renewable energy and its strategy to achieve the national energy target by 2030. As well, the chapter also gives an overview of the status of the PV industry in the Algerian market and the legislative and institutional structures already underway for the national program of renewable energy.

1.2 State of global renewable energy

Nowadays, promoting renewable energy development and utilization worldwide is becoming a common goal and a concerted effort. Renewable energy plays a pivotal role and an important component in the energy supply, optimizing energy structures effectively, balancing supply and demand contradictions, and protecting the environment by reducing carbon and greenhouse gas emissions [19]. With the accelerated development over the last years of renewable energy in the world, renewable energy has become more adequate and affordable to use in various fields.

Renewable energy is increasingly becoming a significant part of the global energy mix. As of the latest reports [20], approximately one-seventh of the world's primary energy comes from renewable sources, which include a combination of hydropower, solar, wind, and other renewable sources, as presented in Figure 1.1.

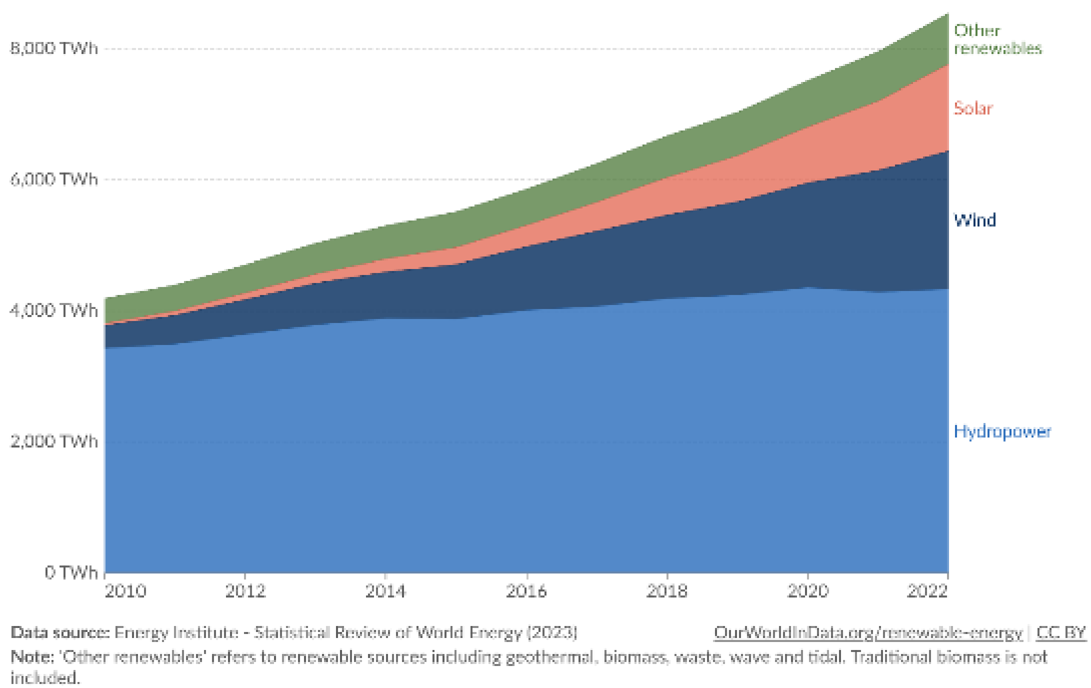


Fig.1.1 Global Renewable Energies Generation in 2022 [21].

1.3 Global Solar Photovoltaic Energy

The global solar energy sector is experiencing significant growth with the installation of a significant amount of renewable capacity. According to the International Renewable Energy Agency (IRENA), global renewable energy capacity in 2020 added more than 260 gigawatts of renewables. Solar and wind in particular have shown remarkable growth, with 127 GW and 111 GW, respectively [IRENA 2021]. Nowadays, due to the rapid expansion of solar energy compared to any other energy technology, which is driven by large-scale projects, and as depicted in Figure 1.2 particularly in China, United States and the European Union [21], could reach 6 terawatts with growth of 20% annually by 2031, replacing fossil fuels by 2050, if it continues in this trend.

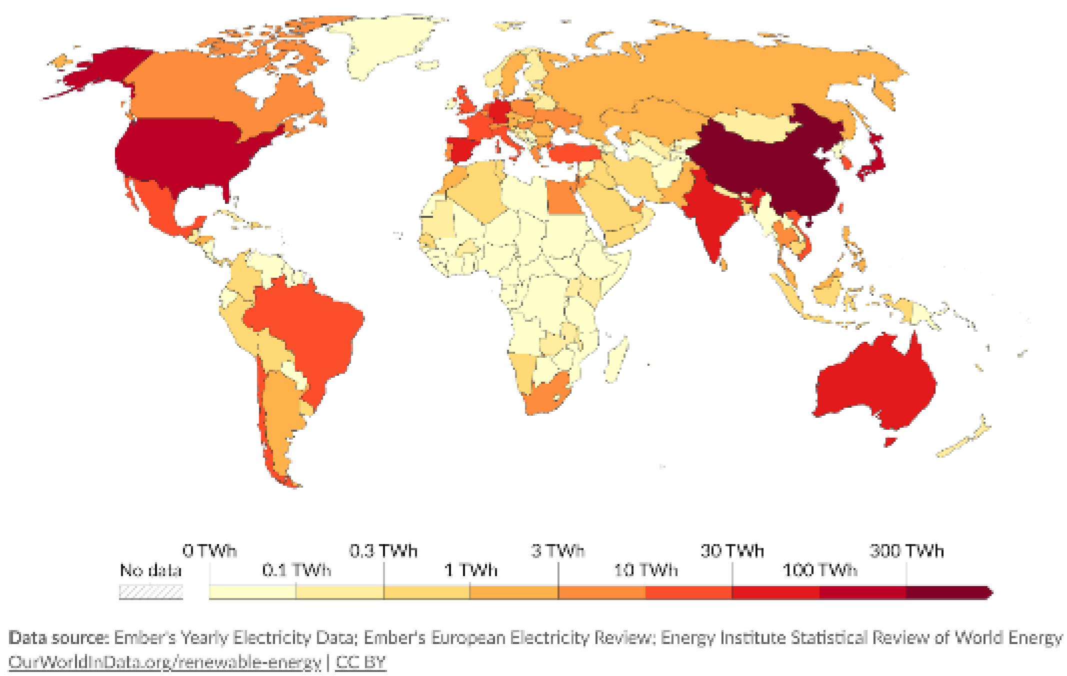


Fig.1.2 Global solar power generation in 2022 [21].

1.4 Status of renewable energy: framework of Algeria

Over the last decade, the price of oil has fallen drastically, severely affecting the national economy. In Algeria, energy production is predominantly marked by dependability on hydrocarbons, comprising 93.6% of its exports. The country generates around 90% of its electricity, primarily from natural gas power plants [22]. The energy transition is becoming a crucial objective for developing nations. To this end, renewable energy serves as a key to achieving these ambitions policies, and initiatives. The Algerian territory possesses a high potential for renewable energy resources such as solar, wind, hydro, biomass, and geothermal energy [22]–[25]. Therefore, the Algerian government moves toward exploiting these resources to achieve diversification of its economy and generate new socioeconomic dynamics [14], [22], [26]. Algeria intends to position itself as a major player in the production of electricity from renewable energy, by exploiting these potentials, the government could effectively cover the nation's increasing demand for energy, as presents in Figure 1.3. In fact, due to the high solar potential in Algeria, solar energy has received particular attention and is currently paving the way as a leading alternative to dependence on fossil fuels.

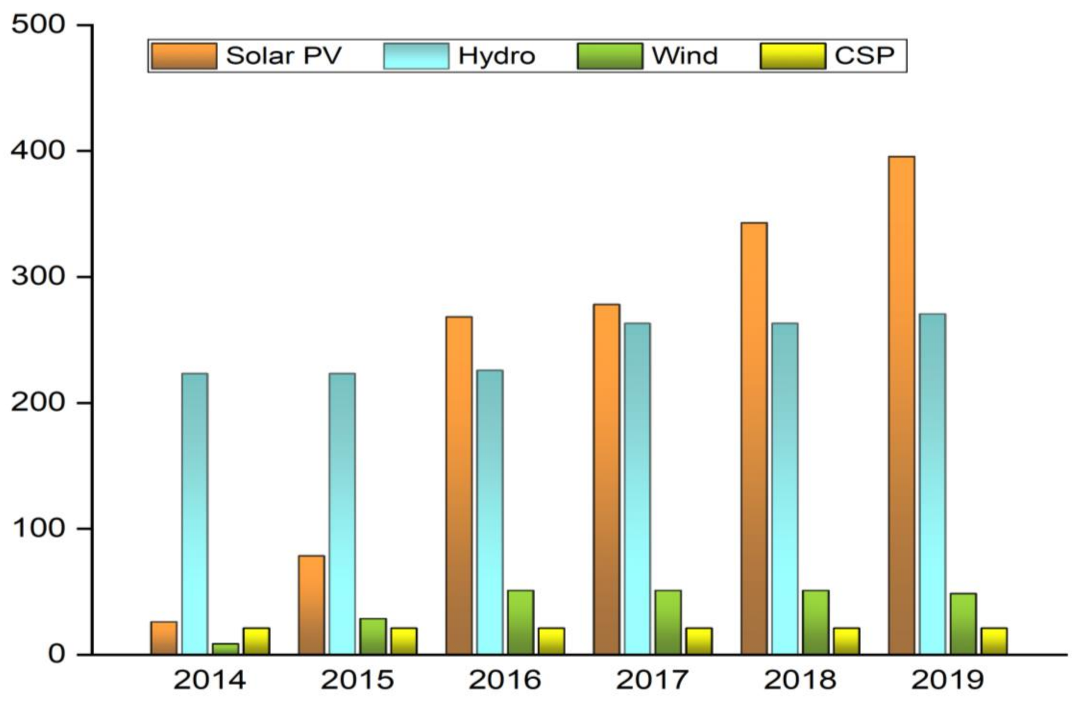


Fig.1.3 Installed capacity of renewable energies from 2014 to 2019 [22].

1.5 Renewable Energy in Algeria: Strategies and targets by 2030

The Algerian government has set an ambitious program to promote renewable energy targets by the National Plan for Renewable Energy 2011–2020 [27]. By 2030, the country aims to reach a clean energy capacity of 22,000 MW (**see Table 1.1**) [27]–[29]. As part of this program, the main focus is on photovoltaic energy and wind energy.

Tab.1.1 Renewable energy program and targets by 2030 [27].

	1st Period (2015–2020)		**2nd Period (2021–2030)**			
Energy Source	**MW**	**%**	**MW**	**%**	**Total (MW)**	**%**
Photovoltaic	3000	66.3	10575	60.52	13.575	61.70
Wind Power	1010	22.32	4000	22.89	5010	22.77
Solar Concentrator	/	/	2000	11.44	2000	9.09
Biomass	360	7.95	640	3.66	1000	4.55
Cogeneration	150	3.31	250	1.43	400	1.82
Geothermal	5	0.11	10	0.06	15	0.07
Total	**4525**		**17475**		**22000**	

In February 2011, the Algerian government introduced its first national program for the development and promotion of renewable energies and energy efficiency (PNEREE) [30]. The Ministry of Energy and Mines (MEM) estimates that by 2030, 40% of electricity generation capacity will come from renewable sources, as presented in Figure 1.4. To achieve this target, the government will ensure a renewable electricity production capacity of 22,000 MW, with 10,000 MW dedicated to export [13], [27], [29]. The national RE program for installation was planned in three phases. First, the initial phase (2011–2013) involved establishing pilot projects. Second, the second phase (2014–2015) focused on developing more projects. And finally, the third phase (2016–2020) is dedicated to completing large-scale RE projects. Furthermore, the program plans to install 10 GW of RE energy exports from 2021 to 2030 [13], [29] .

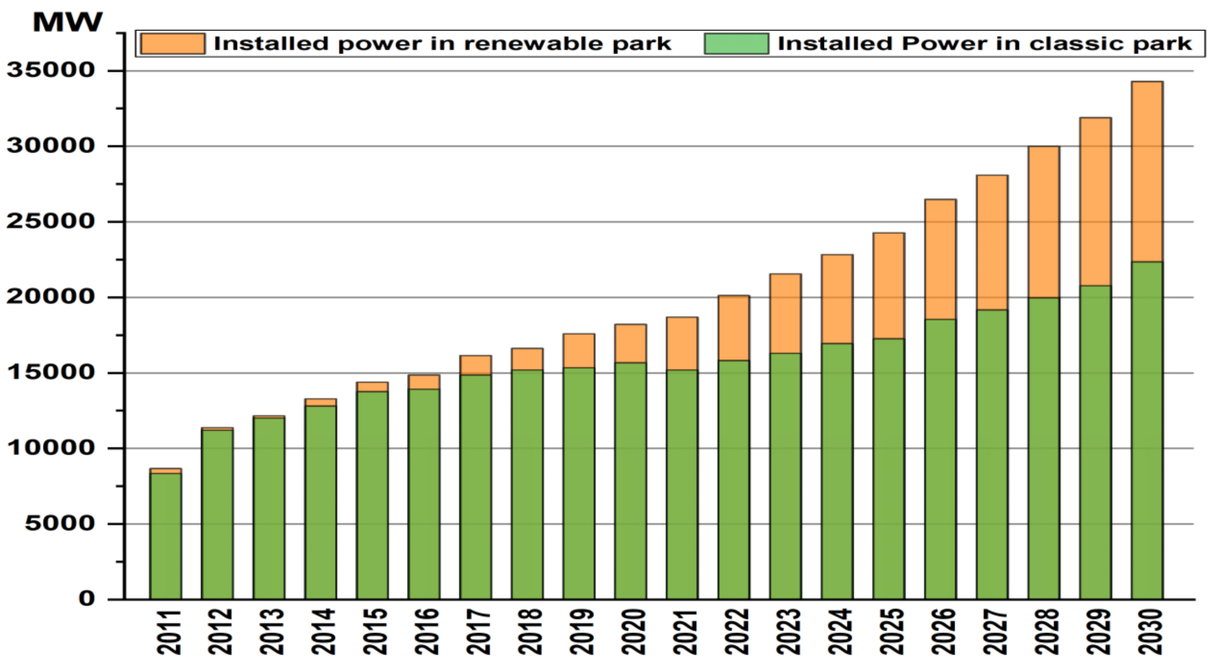


Fig.1.4 National Park evolution for electrical production [29].

1.6 Potential, Evolution and Perspectives of solar energy in Algeria

Recent research performed in Algeria reveals that renewable energies have an important potential for power generation, especially solar photovoltaic, for supplying local electricity as well as for export to the European market [9], [13], [14], [22], [23], [31]–[33].

In addition, and due to its strategic position, large area, and variety of climates, that change gradually over the country's territory that comprised three zones: The coastal area, High plains, and Sahara. The country receives direct irradiation estimated at 169,440 kW/m²/year, with a potential generation of 3000 kWh/year. [13], [27], [34]. Geographically, the desert occupies a total area of 2,048,297 km^2, approximately 86% of the total area of the whole country, which is known for its high solar irradiation and temperature. On the other hand, the country holds a long high solar potential, with a sunshine duration of more than 3000 hours/year over the quasi-total national territory and may reach 3900 h (high plains and Sahara) as presented in Table 1.2 and Figure 1.5 [14], [31], [35].

Tab.1.2 Solar potential in Algeria [31].

Areas		**Coastal area**	**High plains**	**Sahara**
Surface	(%)	4	10	86
Area	(Km²)	95.27	238.174	2.048.297
Mean daily sunshine duration	(h)	7.26	8.22	9.59
Average sunshine duration	(h/year)	2650	3000	3500
Received average energy	(h/year)	1700	1900	2650
Solar daily energy density	(kWh/m²)	4.66	5.21	7.26

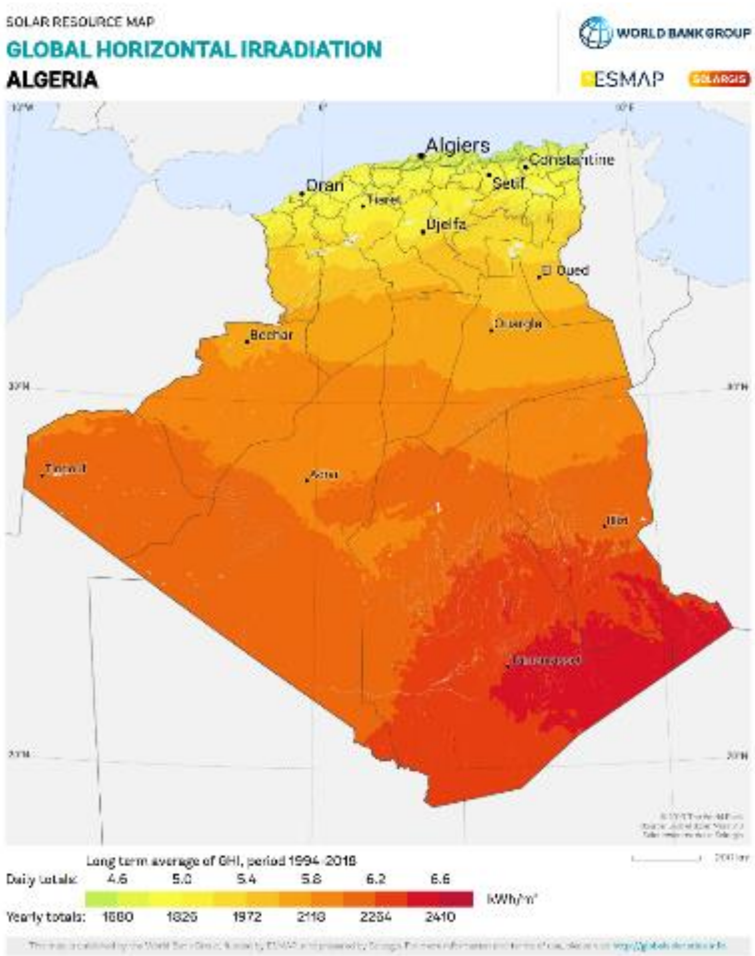


Fig.1.5 Map of global horizontal irradiation of Algeria [36].

1.7 Solar capacity installed for National Program for Renewable Energy

The government planned significant infrastructure and financial investments, successfully transitioning to renewable energy sources.

The expanded Algerian efforts for the National Plan for Renewable Energy were installed in 2011 the first solar plant. Since then, the program has evolved by implementing 22 plants, with a capacity of 423 MW by the end of 2019, from the large project consisting of 60 photovoltaic plants, as listed in Table 1.3. Recently, in 2022, total capacity generation reached 599 MW. In the total power generation, solar power capacity exhibited remarkable growth between 2012 and 2022, from 25 MW in 2012 to 460 MW in 2022 [36], as presented in Figure 1.6.

Table.1.3 Installed solar generation stations in Algeria [14], [22]

PV Central	Location	Surface (Hectare)	Capacity (MW)	Commissioning year
Oued Nechou	Ghardaia	05	1.1	2014
Adrar	Adrar	40	20	2015
Kabertene	Adrar	06	03	2015
Tamnrasset	Tamnrasset	26	13	2015
Djanet	Illizi	06	03	2015
Tindouf	Tindouf	18	09	2015
In Salah	Tamnrasset	10	05	2016
Timimoune	Adrar	18	09	2016
Reggan	Adrar	10	05	2016
Zaouiat Kounta	Adrar	12	06	2016
Aoulef	Adrar	10	05	2016
Serdret Leghzel	Naama	32	20	2016
Oued El Kebrit	Souk Ahras	20	15	2016
Ain Skhouna	Saida	60	30	2016
Telagh	Sidi Bel Abbes	30	12	2016
Labioh Sidi Chikh	El Bayadh	40	23	2016

Ain El Bel 1 and 2	Djelfa	120	53	2016 and 2017
Lekhneg 1 and 2	Laghouat	120	60	2016 and 2017
El Hadjira	Ouargla	60	30	2017
Ain El Melh	M'Sila	40	20	2017
Oued El Ma	Batna	-	02	2017

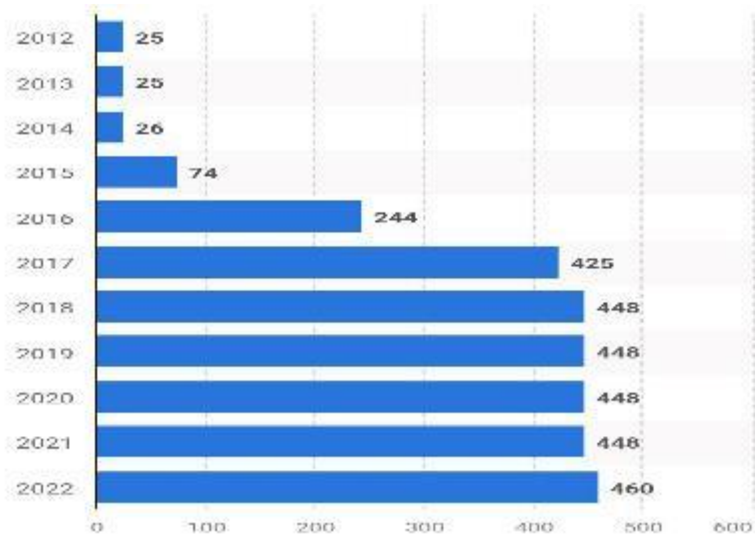


Fig.1.6 Solar power capacity in Algeria from 2012 to 2022 in Mw [36].

1.8 Status of PV industry in the Algerian market

In the last years, Algeria has not had a local PV manufacturer. All installed PV modules during pilot projects from 2011 to 2013 were imported from foreign countries like China, Germany, Spain, and Japan, causing the increased cost of PV systems [14], [22]. For these reasons, the Algerian government announced cooperation with foreign investment for its renewable projects, besides partnership agreements for constructing new PV module factories in Algeria. Nowadays, the country supports solar module manufacturing companies by providing facilities, paving the way for 100% local production in terms of competitiveness, and meeting the requirements of the local market in systems for large solar projects. Several solar module factories have been established in Algeria by various companies, such as Condor, ALPV, Aures Solaire, and ENIE, to serve national solar projects as presented in Table 1.4 [13].

Tab.1.4 Solar module factories in Algeria [13].

Company	Capacity (MW)	Location	Commissioning year
ALPV	12	Batna	2010
Condor	130	Bordj Bou Arreridj	2013
Aures Solaire	50	Sidi Bel Abbes	2016
ENIE	25	Sidi Bel Abbes	2016
Aures Solaire	30	Sidi Bel Abbes	2017
Milltech	100	Mila	2020 (Under construction)

The Algerian electronics company Condor is a significant player in the solar energy sector, operating a solar module factory with a capacity of 130 MW. The company is considered a leader in the Algerian market by its capacity of production of 50 MW per year. Moreover, in 2019, the company was chosen to construct a 50 MW solar power plant. Aurés Solaire Company consists of two manufacturing units with production capacities of 50 MW in Sidi Bel Abbes and 30 MW in Batna. Additionally, the state-owned ENIE, located in Sidi Bel Abbes, has a production capacity of 25 MW per year. In contrast, the ALPV in Batna contributes an annual capacity of 12 MW. Currently, particular efforts are being put underway into building a Milltech solar module manufacturing facility with a 100 MW annual capacity in Chelghoum El Aid, northeast Algeria.

1.9 Legislative and institutional structures for the energy transition

The legislative and regulatory texts governing renewable energies development in Algeria focus on promoting sustainable development and integrating renewable energy into the country's energy strategy. These initiatives reflect Algeria's commitment to transitioning towards cleaner and more sustainable energy sources while attracting investments and promoting renewable energy development in the country. To this end, the Algerian government established several public institutions to support this change by involving institutional structures in the energy transition:

Ministry of Environment and Renewable Energy (MERE): is responsible for environmental policies and the development of renewable energy initiatives [37].

Commission for Renewable Energies and Energy Efficiency (CEREFE): the Commission is dedicated to developing a national policy in the field of renewable energy and energy efficiency, as well as evaluating its implementation [30].

Directorate of Development, Promotion, and Valorization of Renewable Energy: is responsible for the implementation of strategies and policies aimed at promoting and enhancing the use of renewable energy [38].

Directorate of Renewable Energy and Energy Efficiency: is part of the Ministry of Energy Transition and Renewable Energies. The Directorate is responsible for managing and implementing the Algerian energy transition plan, focusing on the deployment of large-scale renewables. On the other hand, it works alongside other institutions to develop and implement Renewable Energy and Energy Efficiency programs [38].

Commission for Energy and Gas Regulation Algeria (CREG): is Algeria's energy regulator, responsible for integrating and regulating renewable energy in the country's energy market [34].

Renewable Energy Development Center (CDER): is a research center focused on developing renewable energies. It encompasses various divisions dedicated to solar photovoltaic, wind, solar thermal, and geothermal, including hydrogen as a renewable energy source. The CDER comprises three units of research, highlighted by:

Research Unit for Renewable Energies in Saharan Region (URERMS): is a key institution in Algeria dedicated to renewable energy research in Saharan environments. It focuses on the evaluation and development of solar, wind, and biomass resources by collecting, exploiting, and analyzing all the data necessary for a precise assessment of solar, wind, and biomass in the Saharan regions. In addition, the unit contributes to the national program for scientific research in renewable energies, set by the Algerian state [39].

Applied Research Unit for Renewable Energies (URAER): is focused on applied research in renewable energies. The URAER aims to become a platform for experimentation and communication on local achievements in renewable energy. The unit contributes to developing renewable energy technologies and collaborates with universities and other research centers for research and training in this field [40].

Solar Equipments Development Unit (UDES): is an Algerian institution that specializes in the development of solar equipment. UDES aims to design, size, and optimize renewable energy equipment for the production of heat, electricity, cold, and water treatment. In addition, the research unit implements characterization, testing, quality, and conformity controls to ensure qualification, approval, and hence certification of the equipment developed [41].

Shariket Kahraba Wa Taket Moutadjadida (SKTM): is a sub-division of Sonelgaz, specializing in electricity generation, development of electrical infrastructure, and marketing the energy produced for the distribution subsidiaries. In addition, it plays a crucial role in managing remote power plants and exploiting solar energy in its various forms in the south of Algeria, including photovoltaic and thermal energy. The SKTM has established several projects recently, such as the SKTM Solar PV Park with a capacity of 13 MW in Tamanrasset, and Hybrid Solar Projects with a total capacity of 50 MW [42].

1.10 Conclusion

Desert area presents a typical geographic profile for solar generation potential: abundant sunshine, low humidity and precipitation, and vast unused flat areas near grid networks. Based on these conditions, the potential for power generation is enormous relative to regional and global energy needs. It is estimated that approximately 10% of the Algerian Sahara area could supply enough energy to meet EU demand [14]. For these reasons, the Algerian government is paving the way for large-scale projects. Currently, the use of solar photovoltaic technology has become easier, affordable, and safer for various applications, from PV panels, PV systems to large-scale installations, the next chapter will deeply discuss the PV systems and its applications.

CHAPTER
II

Solar Photovoltaic System and Applications

2.1 Introductions

Solar photovoltaic technology is one of the many forms of renewable energy and the most mature. Since PV systems can make a significant contribution to a sustainable energy system, they have become the most affordable choice as a source of renewable energy for various electrification applications such as solar home systems, lighting applications, solar charging stations, water pumping systems, smart micro-grids, etc. [8], [43].

The power of solar radiation is harnessed through various subcomponents in a solar PV system, where all systems function together to generate electricity. The PV system consists of multiple panels that can be connected in series or parallel to generate the required power [44]. Once controlled, the energy produced is converted, distributed, and stored using additional components. The components required may vary depending on the system's functional and operational needs. Typically, the configuration of PV systems depends on usage patterns, operational requirements, component topologies, and load requirements [8], [44], [45].

The chapter gives a comprehensive overview of solar photovoltaic (PV) systems and their types, providing a detailed understanding of their main components (cells, panels, inverters, and batteries). Moreover, it presents a deep demonstration of the PV system topology and configuration, illustrated through case studies. The performance evaluation of PV systems has been detailed through a specific analysis technique based on the IEC 61724 standard. Additionally, for successful and sustainable investments in solar photovoltaic (PV) systems, particularly on large scales, the chapter highlights factors that are taken into consideration when selecting the best location for a photovoltaic power plant. These factors set the stage for the PV system application which will be thoroughly taken as a case study in Chapter 4.

2.2 Photovoltaic systems

A solar PV system is one of the world's fastest-growing energy sources, potentially producing around 50 GW by 2030 [46]. Generally, solar PV systems are divided into two types: standalone (off-grid) and grid-connected (on-grid). Typically, PV systems consist of a PV array, system (inverter), and load as presented in Fig 2.1.

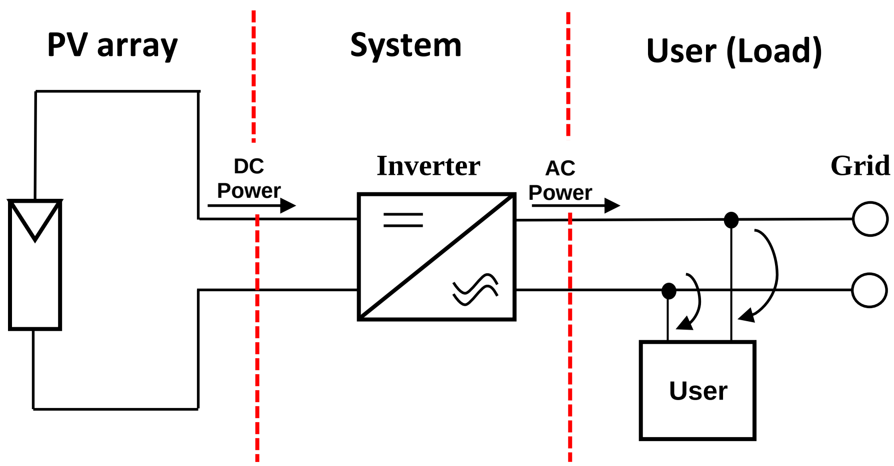


Fig. 2.1 Diagram of solar Photovoltaic system [44].

2.2.1 Off-grid systems (stand-alone)

An off-grid (stand-alone) solar electric system is designed as an alternative to a conventional power supply. These systems utilize solar panels to generate electricity, charging solar batteries to store energy until it's needed. Off-grid solar photovoltaic (PV) systems are typically deployed in rural or remote areas where there is no access to traditional power sources due to the high cost of grid extension [47]. These systems provide energy independence that can be combined with a generator for backup power. Off-grid systems require careful planning and sizing to ensure that they can effectively meet the energy requirements. The size of off-grid systems can range from simple configurations comprising a single PV module, battery, and controller to large systems incorporating advanced control equipment and large backup generator sets to meet energy demands (as presented in Figure 2.2) [44], [48], [49].

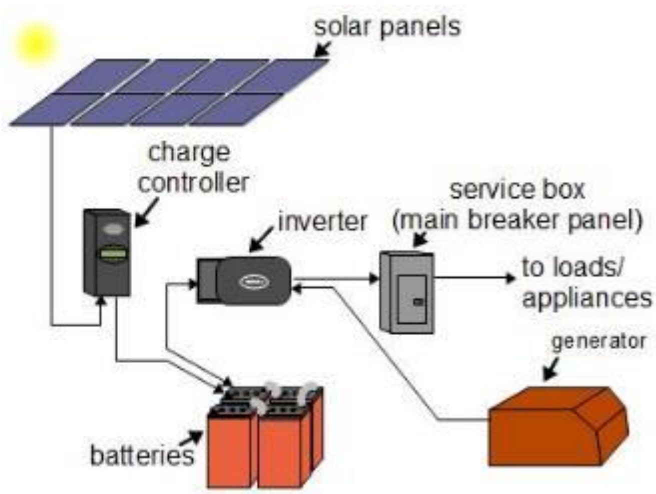


Fig 2.2 An off- grid solar photovoltaic (PV) system [47].

2.2.2 Grid-connected systems

A grid-connected (Grid-tied) solar photovoltaic (PV) system is a type of solar power system that is designed to operate in parallel with the utility grid. Grid-connected systems are normally found in urban or rural areas near electrical networks that have readily available mains supplies, and instead of storing the electricity generated by the PV system in batteries, the power is fed back into the grid [50]. Among the benefits of these systems are does not costly, have fewer components, with reduced maintenance needs, and do not require additional batteries compared to off-grid PV systems. In addition, the main components of a grid-connected PV system include the PV array, inverter, and metering system. Besides these major components, the grid-connected (PV) system requires connection equipment such as cables, combiner boxes, protection devices, switches, and lightning protection (as illustrated in Figure 2.3) [8], [44], [51]. Nowadays, on-grid systems are increasingly used in isolated sites for a wide range of applications as large-scale power plants, and that makes a significant contribution to the energy mix.

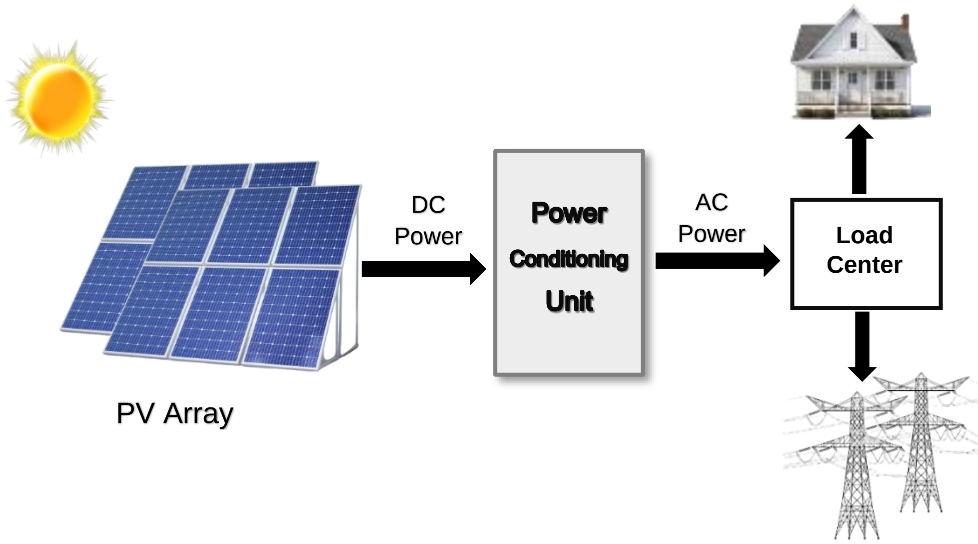


Fig 2.3 A grid-connected solar photovoltaic (PV) [52]

2.3 Components of Photovoltaic (PV) Systems

2.3.1 PV Cells, Modules, Strings, and Arrays

- **PV Cells**

The PV cell is the basic part of the PV system that consists of photovoltaic cells, modules, and arrays. For photovoltaic applications, PV cells of identical characteristics are connected electrically in series, which form a PV module.

In series, the cell's voltages increase while the current stays constant where the current of the module is equal to the current of one cell [44], [52].

- **PV module: specification, Standards, and Certifications**

PV module is the most important element in the solar photovoltaic system. The PV module plays an important role in the size of the inverter in the PV system. Therefore, to guarantee optimal performance and meeting the energy requirements of the system the careful selection of the PV module is crucial in terms of its specifications, certifications, and warranty. On the other hand, it is important to ensure that the PV modules and the electrical installation are safe and in good quality to avoid risks about safety and long term operation [44], [52].

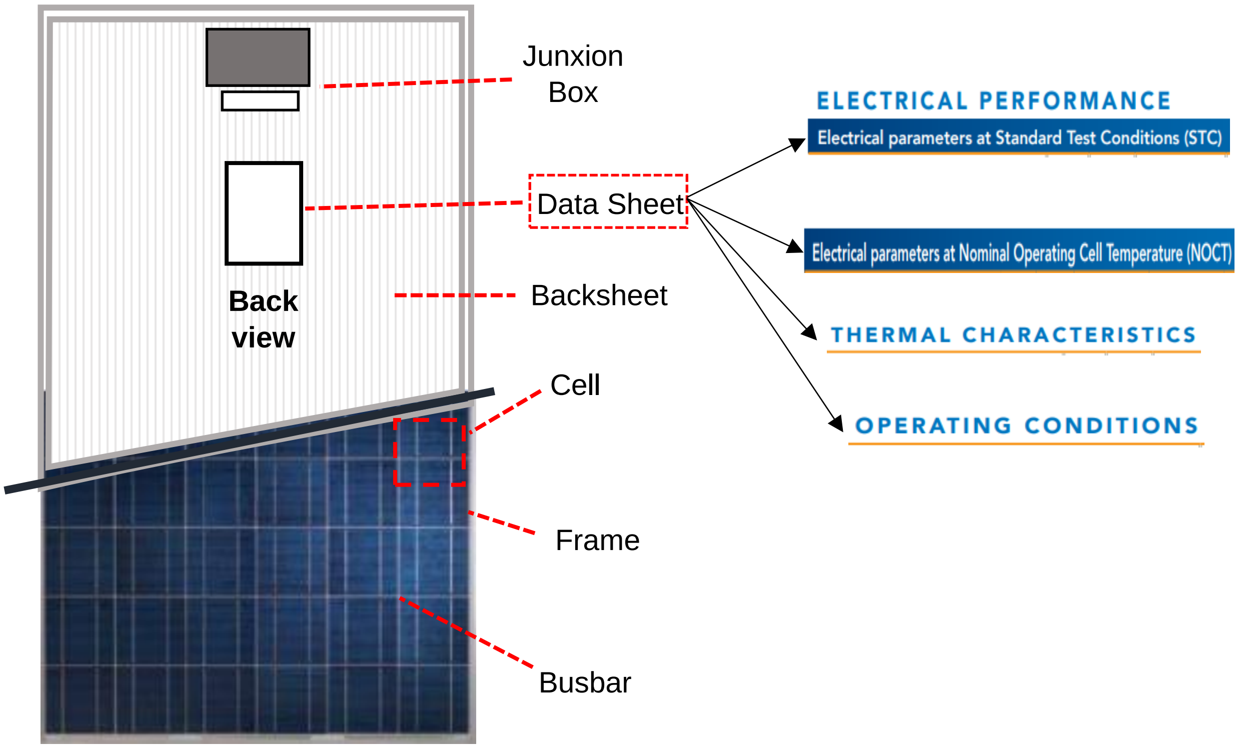


Fig. 2.4 PV module components [53].

Standard Test Conditions (STC)

All PV modules are typically evaluated at standard test conditions (STC) to define their electrical performance and specifications, given by the International Electrotechnical Commission (IEC), to provide information on the maximum power output, voltage, current, and efficiency. The STC consists of specific laboratory conditions in which measurement tests are conducted at a cell temperature of 25°C, an incident solar irradiance level of 1000 W/m², and an Air Mass 1.5 spectral distribution. In addition, some standards, such as IEC 61215, IEC 61646, and IEC 61730, that are related to design and safety qualifications, are required for approval tests on photovoltaic module. Generally, manufacturers use the STC as a way of comparing the different electrical performances of cells and modules. However, it is important to note that the STC is not always achievable to outdoor conditions [53], [54] . Therefore, a careful comparison between the datasheets of photovoltaic modules ensures a good choice for the energy needed, the installation region, and environmental conditions.

ELECTRICAL PERFORMANCE

Electrical parameters at Standard Test Conditions (STC)

Module type			YL245P-29b
Power output	P_{max}	**W**	245
Power output tolerances	Δ P_{max}	**%**	-0 / +3
Module efficiency	η	**%**	15.0
Voltage at Pmax	V_{mpp}	**V**	29.6
Current at Pmax	I_{mpp}	**A**	8.28
Open-circuit voltage	V_{oc}	**V**	37.5
Short-circuit current	I_{sc}	**A**	8.83

STC: 1000W/m² irradiance, 25°C cell temperature, AM 1.5g

Rated of maximum output power at STC

Produced power above or below its rated capacity

Rated Current and Voltage at P_{max}

Maximum voltage with no load

Rated Current at short circuit measurement

The calculation of system yield, inverter size, and system component dimensions relies significantly on electrical parameters, including P_{max}, V_{max}, I_{max}, I_{sc}, and efficiency determined at STC and NOCT conditions. These factors play an important role to determine the overall performance and efficiency of the electrical system.

Nominal Operating Temperature (NOCT)

Nominal Operating Temperature (NOCT) is a measurement referring to the operational conditions of solar cells that is defined as the solar panel temperature at specific environmental standards at an air temperature of 20°C, an incident solar irradiance of 800 W/m², and a wind velocity of 1 m/s. Generally, the NOCT standard is the closest standard to operational conditions [55], [56].

Electrical parameters at Nominal Operating Cell Temperature (NOCT)

Power output	P_{max}	**W**	178.7
Voltage at Pmax	V_{mpp}	**V**	27.0
Current at Pmax	I_{mpp}	**A**	6.62
Open-circuit voltage	V_{oc}	**V**	34.6
Short-circuit current	I_{sc}	**A**	7.14

The electrical parameters are determined at NOCT conditions at: 800W/m² irradiance, 20°C ambient temperature, 1m/s wind speed

Thermal Characteristics

Nominal operating cell temperature	NOCT	**°C**	46 +/- 2
Temperature coefficient of P_{max}	γ	**%/°C**	-0.42
Temperature coefficient of V_{oc}	βV_{oc}	**%/°C**	-0.32
Temperature coefficient of I_{sc}	αI_{sc}	**%/°C**	0.05
Temperature coefficient of V_{mpp}	βV_{mpp}	**%/°C**	-0.42

For every 1 degree (°C) increase in temperature from 20°C, P_{max}, V_{oc} and V_{mpp} decrease by -0.42%, -0.32% and -0.42 % respectively. with an increase of 0.05% in Isc.

Operating Conditions

Max. system voltage	1000 V_{DC}
Max. series fuse rating	15 A
Limiting reverse current	15 A
Operating temperature range	- 40 to 85 °C

Required to ensure the safety of PV array size

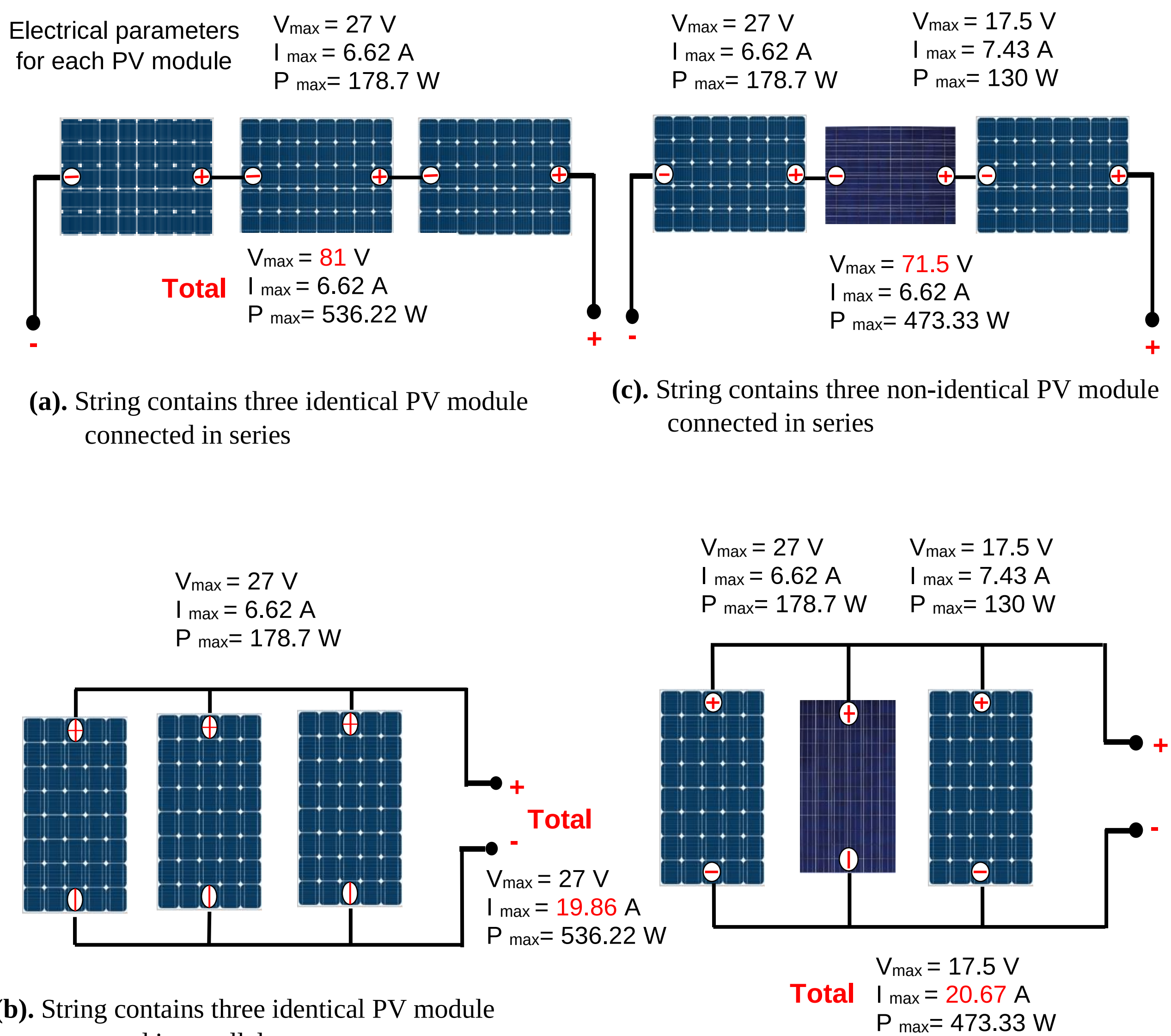
To determine requirements of system protection

- **String of PV modules**

PV string consists of PV modules that are connected in series to produce higher voltages and output power. In contrast, the output current is determined by the lowest current in the module's string. Therefore, to obtain the desired output voltage, it should determine the number of modules connected in series. In the case of modules that are connected in parallel, the output current increases (the sum of the modules' current) while the output voltage is determined by the single module, as presented in Figure 2.5 [44], [57].

- **Photovoltaic PV Array**

To obtain the desired current, strings that are connected in parallel form an array; in cases where strings are connected in parallel, the output current will be assembled from the individual strings. In the case of strings comprising non-identical modules, the output current of a given string is



(a). String contains three identical PV module connected in series

(c). String contains three non-identical PV module connected in series

(b). String contains three identical PV module connected in parallel

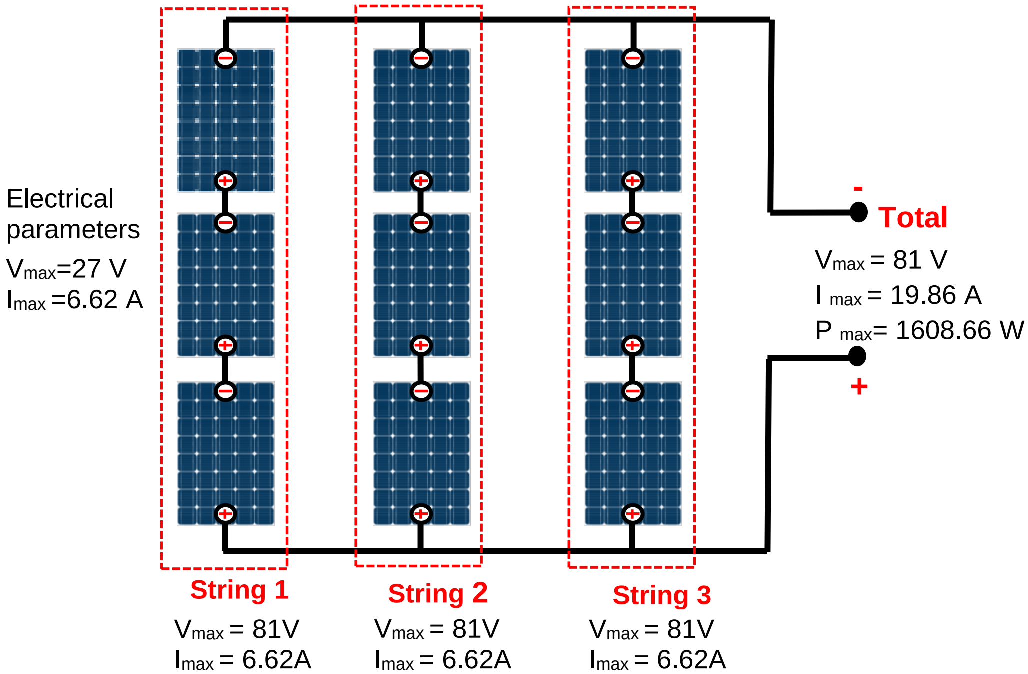
(d). String contains three non-identical PV module connected in parallel

Fig. 2.5 Different String connections with identical and non-identical PV modules [7].

determined by the lowest output current value, which is then assembled with the next string. The output voltage is also determined by their lowest value in the string, as demonstrated in Figure 2.6.

Additionally, series and parallel configurations of connected PV modules are referred to as PV arrays.

(a) *Case of PV Array with identical Strings*



(b) *Case of PV Array with identical and non-identical String*

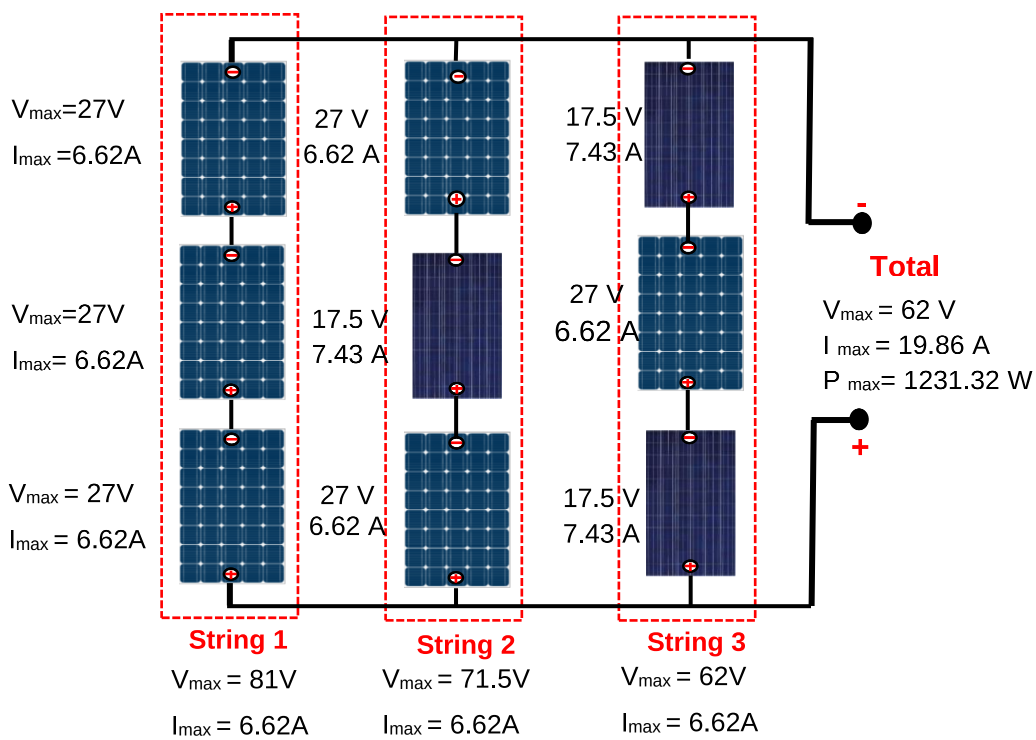


Fig. 2.6 Cases of PV Arrays with identical and non-identical strings [7].

As a conclusion, Figure 2.4 presents clearly the assembled steps from a single PV cell to a PV array. The connected PV cells in series form a PV module that consists of 40 PV cells. For a PV string, three modules are in series that increase the voltage, where the V_{tot} represents the sum of the voltages for each module in series. In addition, the two strings connected in parallel form a PV array. The output current of the array (I_{tot}) becomes the sum of the currents through each string.

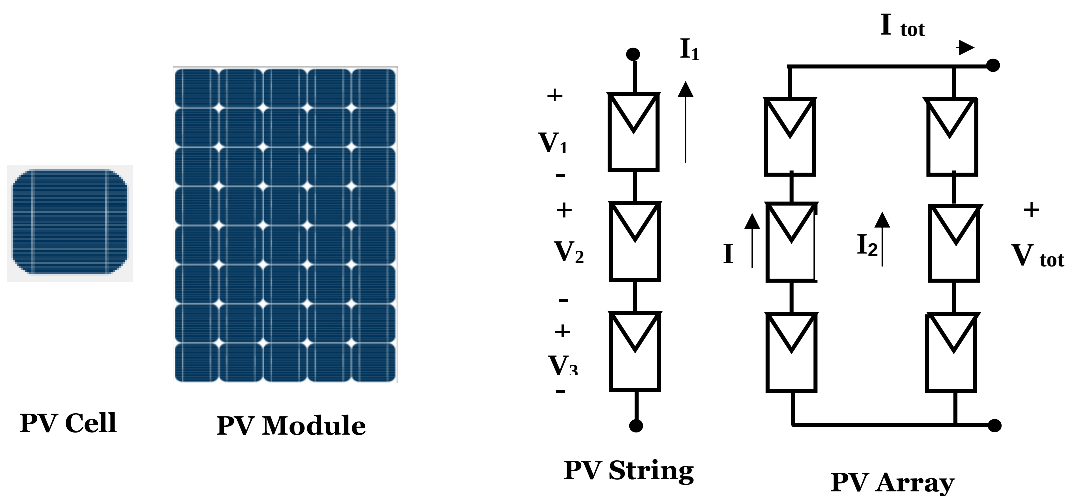


Fig 2.7 PV cell, module, string and PV array [8].

2.3.2 Inverters DC - AC

Photovoltaic arrays typically produce direct current (DC) electricity, while grids and most electrical loads require alternating current (AC) as shown in Figure 2.8. Inverters play a main role in this conversion process, converting the direct current (DC) generated into alternating current (AC) with the required frequency of either 50 Hz or 60 Hz, which is the standard form of electricity used in the electrical grid and other applications. The selection of appropriate inverter types for the solar system depends on specific factors related to the requirements and design of the PV system, such as system size, power levels, and other parameters [44], [58]. Table 2.1 provides a comprehensive overview of the inverter types, including their advantages, applications, and characteristics [44], [59]–[61].

Tab 2.1 Solar inverter types [44], [59]–[61].

Inverter Type	Application	Description	Advantages	Considerations
String Inverters	Strings, smaller installations	Used to convert DC to AC in string and small systems ranging from 1kWp to 11 kWp.	Suitable for smaller installations, Cost-effective, easy maintenance, and high efficiency.	A single shaded or malfunctioning module can affect the entire string's performance.
Micro-inverters	Individual solar panels	Designed to be mounted on the back of the PV module, converting DC to AC at the module level.	Panel optimization (MPPT), by reducing the impact of shading on individual panels, improves safety.	higher cost compared to string inverters
Central inverters	Used in large-scale PV systems	These inverters convert DC electricity from multiple strings of solar panels into AC electricity.	High efficiency and cost-effective for large-scale installations with high reliability	Susceptible to loss, the whole array output can drop if a single panel within a string is shaded or malfunctions.
Hybrid Inverters	Usually used in off-grid systems	These inverters work in both directions, managing the energy from solar panels and energy storage systems that allow the use of solar power and energy storage simultaneously.	work with both solar panels and energy storage systems, reduce dependence on the grid, Integration with Smart Home Systems	High cost, more complex in installations
Three-Phase Inverters	Used in commercial and industrial	These inverters convert DC source into a three-phase AC output	Suitable for larger installations, efficient for three-phase grid connections	high cost, higher complexity in maintenance

Parameters	Specifications
Model	
Input DC	
Maximum DC input power	
Input Voltage range	
Starting Voltage	
Maximum DC input current	
MPPT Voltage range	

Maximum power that can be produced

The range of voltages that the inverter can operate

Minimum DC voltage required to start the inverter

Maximum DC current that can be managed from the solar system

Voltage range that the inverter can optimize the power output

Output AC	
Rated output power	
Nominal output Voltage	
Maximum output Current	
Nominal output Frequency	
Efficiency	

Maximum power delivered under normal operating conditions

AC voltage that the inverter produces

AC voltage the inverter is designed to connect to

Typically, 50Hz or 60Hz

The highest efficiency the inverter can be achieved

Operating Conditions	
Operating temperature range	
Humidity rate	

Environmental and electrical conditions that define inverter function properly

Mechanical Specifications	
Dimension	
Weight	
Protection	

Physical and structural characteristics of the inverter

IP protection rate against solid and water ingress

Fig.2.9 Electrical and mechanical specifications, operating conditions of solar inverter

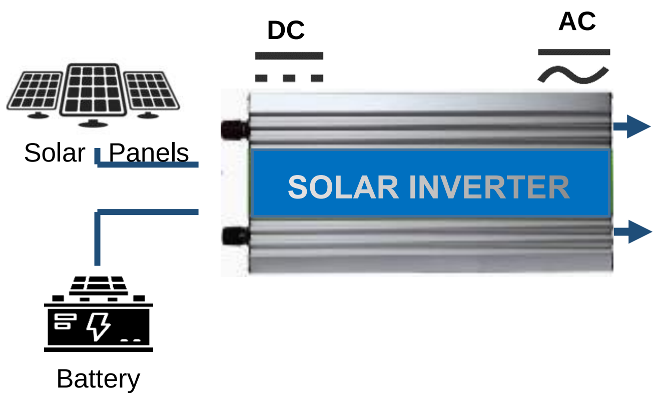


Fig. 2.8 Solar inverter conversion process DC into AC [45].

- **Essential factors to consider for selecting the size of power inverter**

To achieve optimal performance and avoid warranty issues, selecting the right inverter sizes for specific applications in these systems is imperative. To ensure compatibility and maximum efficiency, it should be taken into consideration: **Power requirements** (are determined by determining the load size), **Voltage compatibility** (is ensured by the inverter's input voltage meeting the power source), **Battery capacity** and voltage (for an off-grid system) (are ensures the inverter's input voltage matching the voltage of the battery and by providing sufficient power for batteries), **Load types** (resistive or inductive load) and **Surge capacity** (ensuring that the inverter can handle temporary surge capacity for specific appliances like refrigerators and air conditioners) [62]–[64].

2.3.3 Batteries

Solar batteries are considered an integral part of photovoltaic (PV) systems, which are responsible for storing the excess energy generated by solar panels during sunny periods that can be used at night, during power outages, or when their solar panels do not generate enough electricity on cloudy days. Through stored energy, solar batteries reduce dependence on the grid. Solar batteries are an indispensable component for off-grid systems that provide a continuous power supply [65], [66].

For an on-grid solar power system, adding batteries includes additional costs, maintenance, and considerations. It is crucial to carefully select batteries that are compatible with grid-tied inverters for specific needs and meet local regulations.

- **Types of batteries**

The most familiar types of solar batteries that are available and used in a wide range of applications as stand-alone, and on-grid PV systems are generally found in four main types: **Lead-Acid** (are the oldest type of solar battery and are known for their reliability and low cost), **Lithium-ion** (are increasingly popular due to their high energy density and longer lifespan and require less maintenance), **Nickel-cadmium** (are rechargeable batteries and are suitable for applications in harsh environments with lower density, and requiring high maintenance), and **Flow batteries** (can provide long-duration energy storage and lifespan, due to higher costs it's less used). In terms of cost, performance, lifespan, and environmental impact, each type has different advantages and disadvantages [8], [44], [67].

2.4 Performance evaluation of PV systems

The performance of PV systems is gradually reduced with time, which is affected by various factors, including equipment used, configuration, geographic location, and climatic conditions.
In regions with extreme climates, such as deserts, characterized by harsh environmental factors like high ambient temperatures and solar irradiation, the overall performance of PV systems can be significantly impacted. This leads to accelerated failure modes and degradation within a short timeframe [3], [5], [68], [69]. Chapter 3 provides a comprehensive review and presentation of the effects of these specific climatic conditions on PV systems.

Typically, PV systems performance is analyzed based on IEC 61724. To achieve a reliable and clear output evaluation by using a specific analysis technique throughout the electrical output of the PV system, according to the standard's requirements that consider meteorological conditions, system components, and system design [70], [71].

2.4.1 Energies yields

- **Energy production by the PV system (E_{dc})**

The generated energy (DC) by the PV system on a daily $E_{DC,d}$ or monthly $E_{DC,m}$, basis (kW h) is given as follows [5], [72]:

$$E_{DC,d} = \sum_{t=1}^{t=Tr} E_{DC} \quad \text{And} \quad E_{DC,m} = \sum_{d=1}^{n} E_{DC,d} \tag{1}$$

Where: Tr: is the time period in the day

n: is the number of days in the month.

- **The AC energy generated and delivered (E_{ac})**

After suitable conversion from DC to AC, the energy converted by the inverter is delivered for utility. The energy converted is the same as with the generated energy (DC), where the daily $E_{AC,d}$ or monthly $E_{AC,m}$ energy is given by [5], [73]:

$$E_{AC,d} = \sum_{t=1}^{t=Tr} E_{AC} \quad \text{And} \quad E_{AC,m} = \sum_{d=1}^{n} E_{AC,d} \tag{2}$$

- **Reference yield (Y_r)**

Theoretically, the reference yield is the maximum amount of solar energy available for a specific location , It can also be defined as the ratio between the total quantity of solar radiation arriving at the surface of the solar PV panels HT (kWh/m^2) and the quantity of reference solar irradiance G_{STC} (kW/m^2) [74]–[76], given by:

$$Y_R = \frac{H_T}{G_{STC}} \tag{3}$$

- **Array yield (Y_A)**

Array yield Y_A is defined as the ratio between the total daily or monthly energy generated E_{DC} (kWh) and the rated nominal power P_{nom} (kWp) under standard conditions [5], [77].

$$Y_A = \frac{E_{DC}}{P_{nom}} \tag{4}$$

- **Final yield (Y_f)**

Final yield energy is the total amount of energy a solar system produces EAC (kWh), compared to its rated maximum power capacity at STC Pnom (kWp), over a specific period, typically a year [77], [78].

$$Y_F = \frac{E_{AC}}{P_{nom}} \tag{5}$$

2.6.1 Energies efficiencies

- **PV panel efficiency (η_{PV})**

The proportion of sunlight converted into electricity determines the efficiency of a solar panel [5], [74], [79]. Hence, the instantaneous efficiency of the PV panel is given by:

$$\eta_{PV} = \frac{P_{dC,out}}{G_i * S_{PV}} \tag{6}$$

Where: $P_{dc,out}$ is the output DC power generated by PV panel, and S_{PV} is the PV panel area.

And therefore, the monthly PV panel efficiency is concluded as follows:

$$\eta_{PV,m}(\%) = \left(\frac{E_{dC,m}}{H * S_{PV}}\right) \times 100 \tag{7}$$

Where: H is the total solar irradiance in a month

- **Inverter efficiency (η_{inv})**

Inverter efficiency is defined as the ratio of the output AC power generated by the inverter to the DC power output of the PV array [73], [80], is given by:

$$\eta_{inv} = \left(\frac{E_{AC}}{E_{DC}}\right) \times 100 \tag{8}$$

- **System efficiency (η_{Sys})**

System efficiency (η_{Sys}) is defined by the product of PV panel efficiency and inverter efficiency, as given by [74], [77]:

$$\eta_{sys} = \eta_{PV} * \eta_{inv} \tag{9}$$

- **Performance ratio (PR)**

Performance ratio (PR) in solar systems is a key indicator of the efficiency and quality of solar systems. It indicates the overall effect of the losses on energy production such as operating temperature, inverter efficiency, shading, module orientation, DC/AC cabling losses, and mismatch loss [5], [73], [74], [77]. PR is defined by the ratio between the final yield and the reference yield, is given by:

$$PR = \frac{Y_F}{Y_R} = \frac{E_{AC,d}}{P_{mp(rated)}} / \frac{H}{G_{STC}} \tag{10}$$

Also, the instantaneous performance ratio can be determined by:

$$PR_i = \frac{P_{mp,i}}{P_{mp(rated)}} / \frac{G_i}{G_{STC}} \tag{11}$$

Where: $P_{mp,i}$ the instantaneous power delivered at the maximum power point

G_i instantaneous solar irradiance received

- **Capacity factor (CF)**

It is defined as the actual annual energy output ($E_{AC,a}$) of the PV system divided by the amount of energy that the PV system would generate at full rated power ($P_{mp,rated}$) [5], [72], [81], and is given as:

$$CF = \frac{Y_{F,a}}{24*365} = \frac{E_{AC,a}}{P_{mp(rated)}*8760} \tag{12}$$

2.6.1 Energies losses

Under real operating conditions, energy losses in various PV system components are evaluated using array capture losses and system losses. The array capture loss and system loss comprise thermal loss, system losses in inverters, shadowing and wiring losses, etc [5], [73].

- **Array capture loss (LC)**

It is defined as the difference between reference yield and array yield. Array capture loss occurs from the disparity between actual irradiance and reference irradiance [79], [80], [82].

$$L_C = Y_R - Y_A \tag{13}$$

- **System loss (LS)**

The System losses of the LS system are due to the losses by conversion that are incorporated with the discontinuous operation of the inverter. It can be determined by the difference between array yield and final yield [5], [73].

$$L_S = Y_A - Y_R \tag{14}$$

2.7 Factors and considerations for sustainable Photovoltaic Power Plant investment

For successful and sustainable investment in solar power plants, particularly on a large scale, several factors are taken into account such as location, economic, political, and climatic; further, it can be considered a key points in choosing the optimal location for solar photovoltaic power plant in terms of efficient planning, optimal deployment, energy management, and cost-effectiveness [8], [44], [83], [84]. These factors. By considering these factors, investors can identify factors that they should consider in their decision-making. The most frequent factors as location and climate, are discussed

- **Location**

Large-scale solar power plants are systems that require large extensions of land. On the other hand, it is necessary to carefully choose the land by avoiding areas that are use-restricted, such as reserves, forests, and land that is used for agricultural purposes. Conducting a location assessment by collecting the required information is an important step in the design, installation, and safety of a solar PV system. A site assessment aims to determine the location that incorporates high energy potential in terms of the availability of solar radiation and sunshine duration, considering the ratio and the total amount of energy/PV area. Furthermore, it is advisable to select a site that is easily accessible and near high-voltage electrical networks and water resources. These choices enhance the construction, operation, and maintenance, contributing to the overall efficiency and cost-effectiveness of the solar power plant [83], [85], [86] .

- **Climate**

Considering that climatic factors have a crucial role in determining the suitability of a location for the installation of a photovoltaic (PV) power plant, studying the climate of the place is significant to knowing its characteristics over the years. However, it has an impact on electricity production capacity, and it is imperative to consider these factors in determining and making decisions about the overall output and efficiency [87], [88]. These factors involving solar irradiation, temperature, duration of sunlight, wind speed, and relative humidity, are discussed briefly in Chapter 3.

- **Political**

The decisions made by leaders play a role, in determining the investment in solar power plant installations. Governments promote the growth of energy by offering tax incentives and building trust with investors through political support. Global collaboration also plays a role, in advancing technology and enhancing energy security [83], [89]–[91].

2.6 Conclusion

In summary, and as we discussed above, by taking into consideration the instructions to choose components' quality and sizes for PV systems, solar PV systems can be an alternative source of energy in small and large applications, offering several benefits by using free energy generation, reduction in electricity bills, and energy independence that make it suitable for long-term energy needs. Monitoring these systems is considered an important key to long-term reliability. The next chapter will address the factors affecting PV panels and system performance in harsh conditions like those found in the desert that contribute to the degradation and failure modes of PV panels.

CHAPTER

III

Performance study of photovoltaic panels in Algeria Desert

3.1 Introduction:

Usually, crystalline PV modules consist of six main components, three of which are made of polymers. These polymers are used in the back sheet and encapsulation layers, protecting the solar cells from weather conditions [3]. Nevertheless, utilizing solar PV is not a simple process for energy generation due to degradations occurring in the installed environment, which can result in degradation and /or failure in solar PV panels before they meet the manufacturer warranty that is generally expected by 25 years [5], [92], [93]. Long-term reliability and performance are considered critical concerns, especially for PV modules that operate in specific field conditions, which generally depend upon the type of local climate and its environmental stress factors, whether they are applied sequentially, partially, or in combination [94], [95]. In this regard, recognizing the main parameters directly influencing the module during its field operation is a key success in improving the PV panel's performance and lifetime [11], [96], [97].

Desert is a very appealing region for solar photovoltaic power generation, in terms of the huge availability of solar irradiation, long-time sunshine, and vast unused land. These unique features motivate investments, from simple PV power generation to large scales [3], [92]. On the other hand, these regions also exhibit harsh surrounding conditions, such as high environmental temperatures, high UV

irradiation, sand storms, and other conditions [24]. Among these parameters, numerous factors strongly affect PV module components compared to other climates, resulting in various degradation modes that appear in a short frame time, including encapsulant discoloration, hot spots, delamination, thermo-fatigue, finger discoloration, breakage, etc., that directly reduce their reliability [11], [23], [98]–[100].

The chapter presents an in-depth study of environmental factors influencing the performance and reliability of standard PV panels in the desert. The chapter not only provides the impact of environmental factors on the PV panel's performance but also discusses the different failure modes and degradation that can appear on these PV panels in this region. For this chapter, the Algerian Desert is chosen as a case study due to its particularity of solar irradiation availability and its harsh environmental conditions, which makes it expected to be suitable for energy production. An experimental study was conducted at the unit of renewable energy in Saharan middle (URER-MS).

3.2 Overview of the region

The Algerian Desert is ranked as one of the largest hot deserts in the world. It is located in North Africa, covering over 90% of the Algerian territory, positioned between latitudes 27.01° S and 22.78° N and longitudes 9.39° E and 2.62° E. The region is characterized by a harsh climate with extreme temperatures, notably in hot seasons, with peak values reaching 49°C [23], [32], [101]. Additionally, the area experiences low rainfall, recording less than 100 mm per year. The large size of the Sahara could capture enough solar energy, where the region receives the highest levels of solar irradiance worldwide, with an annual average of 5 kW, possessing high solar potential, with more than 3000 hours of sunshine per year making it a valuable source of solar energy [14], [22].

3.3 Experimental study

An experimental study to collect climatic data and characterize many c-Si PV modules to evaluate their performance has been carried out at the Research Unit of Renewable Energy in the Saharan Middle (URER-MS), Adrar, which is located in Southwestern Algeria, lies at 258 m above sea level and covers a surface area of approximately 424 948 km² between latitudes 27.88°N and longitude - 0.28°W. Southwestern Algeria, through a Solmetric IV tracer and selected PV modules, as shown in Figure 3.1 [23].

Fig 3.1 The experimental study at URER-MS [23].

3.4 Review of Solar radiations influencing the PV panel performance

Solar irradiation represents the radiant energy from the sun and serves as the primary energy source for PV panels. It allows the conversion of sunlight into electricity through the photovoltaic effect. Moreover, it is an energy source that can be measured. Its fluctuation depends on various factors such as weather conditions and location [102]. The incoming solar energy that falls on the surface can be categorized into three main types of radiation based on their characteristics: direct, diffused, and reflected [103], it comes in different forms, including ultraviolet rays, visible light rays, infrared waves, and other forms of energy [103], [104]. The global norm for solar spectrum irradiance ranges from 280 to 4000 nm, with an integrated solar power of 1000 W/m² [4], [93], [105]. The UV range (280–400 nm) comprises only ~4.6% of the overall power, nevertheless, its photons are the most damaging to polymeric materials over time, generating scissions in the fundamental chain bonds of polymers. These scission lead to changes in the properties of the polymer that enhance the accelerated degradation processes of the encapsulant which is highlighted by discoloration[3], [105]. The performance of solar photovoltaic (PV) panels is directly proportional to the amount of solar irradiation they receive. On the other hand, currents produced by PV modules have a linear relationship with solar irradiation wherein, increased incident solar irradiation makes more photons available to move the electrons from the balance band to the conduction band, producing more current [106].

The desert region under consideration exhibits a large amount of available solar irradiation, characterized by intense and prolonged exposure to sunlight with clear sky sunshine throughout the year, as illustrated in Figure 3.2. However, the high amount of solar irradiation is equally accompanied by high UV doses.

As can be seen clearly in Fig 3.3, solar irradiation depends on seasons, where the summer is characterized by high irradiance. Over a year, the highest measured solar irradiation was observed in July reaching a peak of 1200 w/m², where the lowest measured was recorded in winter seasons.

In the summer season, the monthly average of solar irradiation was 1007 W/m², where the highest measured solar irradiation was recorded in July (1309 W/m²). Besides that, the autumn season recorded a monthly average of 841 W/m^2, with a highest value of 1090 W/m² in October. For the winter seasons, which is characterized by low irradiance, where the monthly average of solar irradiation was 640 W/m², considering 780 W/m² as the highest value in February, Respectively, in the spring season, the monthly average solar irradiation was 890 W/m², recording its highest value in May (990 W/m²).

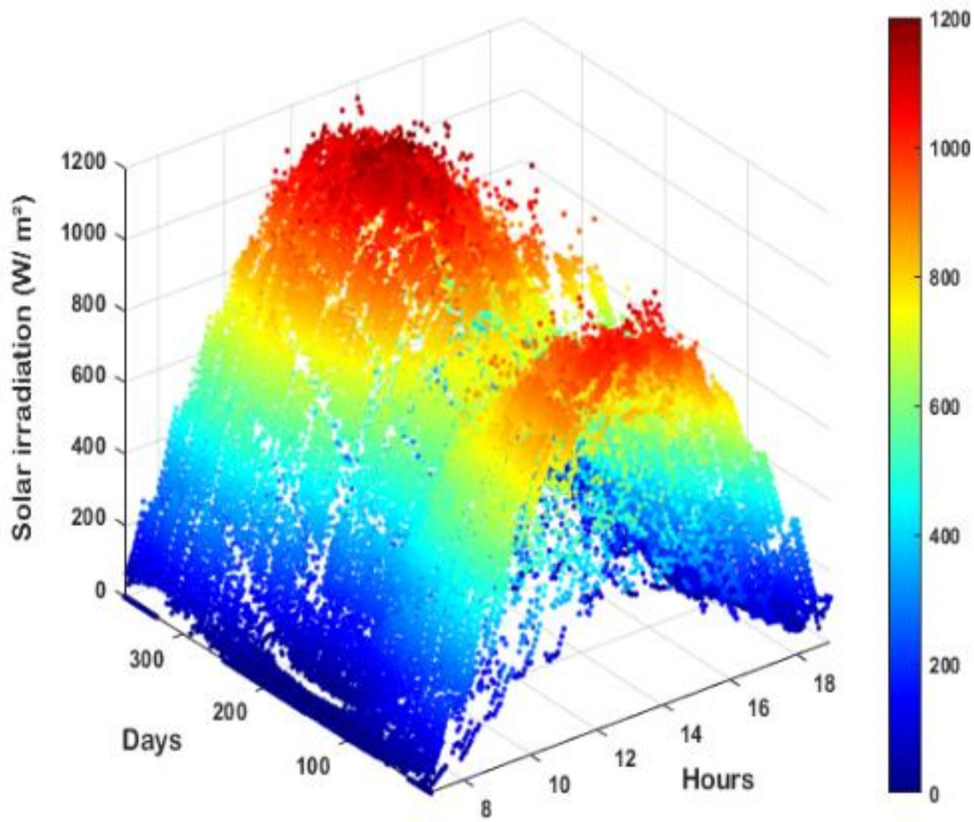


Fig.3.2 Global Solar irradiation in year.

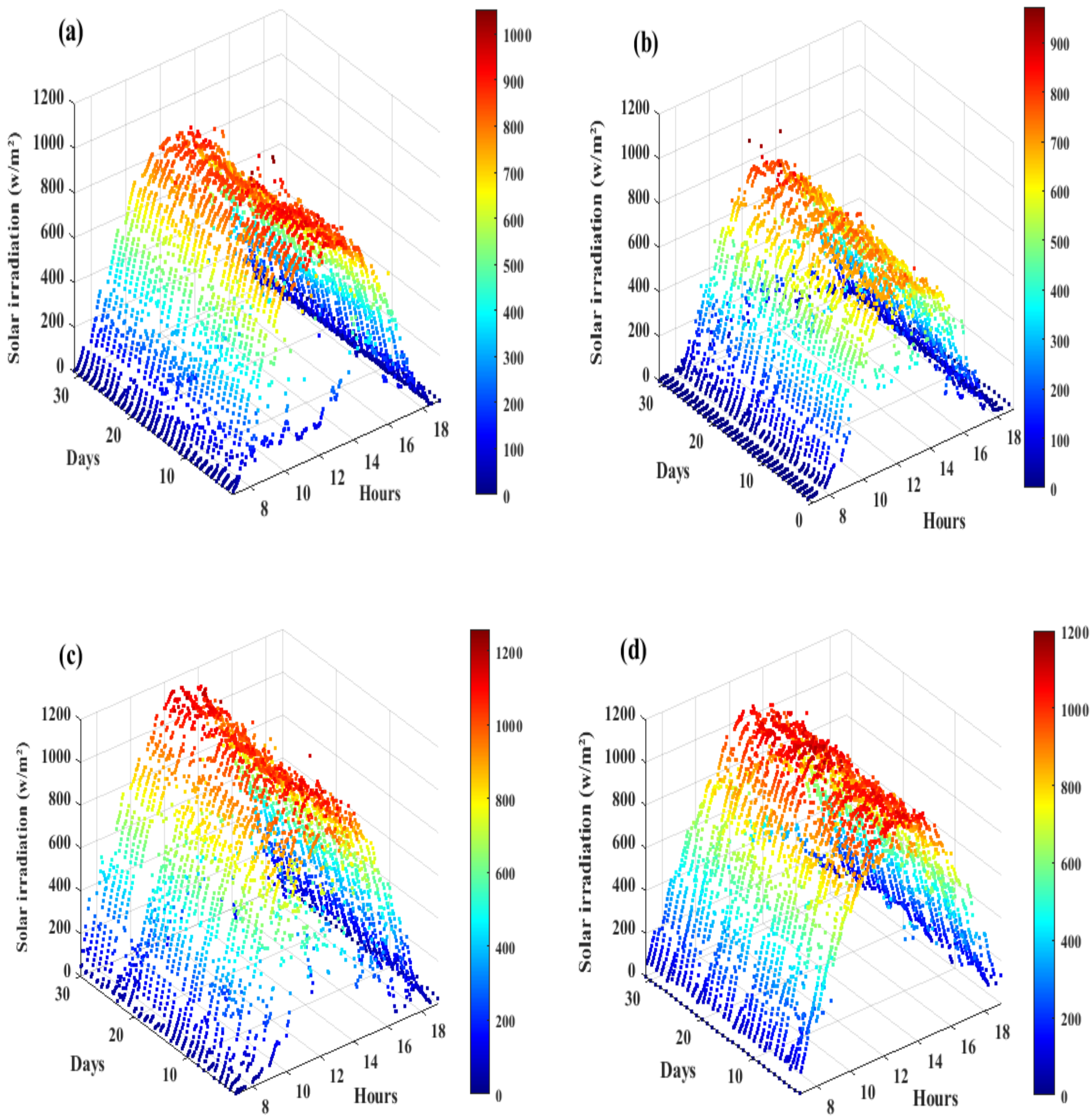


Fig.3.3 Daily solar irradiation for: **(a)** October 2017, **(b)** January 2018, **(c)** April 2018, **(d)** July 2018.

- **Performance evaluation and degradation modes**

In these regions, the most physical defect observed is discoloration, where most PV modules suffer from encapsulant discoloration. Almost all modules older than 5 years are affected by encapsulant yellowing/ browning, as illustrated in Figures 3.6 and 3.7.

An experimental study has been conducted on several c-Si PV modules that have operated for 11 years and suffer discoloration. To investigate the effect of solar irradiation on their electrical parameters, which the encapsulant discoloration is primarily a significant factor in reducing the short-circuit current and also in the decrease in R_{sh}, and hence the output power.
The degradation rate of the electrical performance of the tested panels is evaluated using the following equation 15 [23], [97], [99], [107]:

$$FD(\%) = 1 - \left(\frac{VPdeg}{VPini}\right) \times 100 \quad (15)$$

FD: Degradation Rate for considered parameter.
VP_{deg}: Parameter value after degradation.
VP_{ini}: Initial value of considered parameter.

Tables 3.1 and 3.2 lists the experimental results that were converted and compared to STC for both tested technologies.

- **Polycrystalline PV module**

Tab 3.1 Electrical parameters and degradation rates of tested polycrystalline PV module

Electrical parameters		**STC**	**Measured**	**Degradation rate %**
P_{max}	**(W)**	50	25.05	49.9
V_{mpp}	**(V)**	17.2	12.95	24.7
I_{mpp}	**(A)**	2.9	1.93	33.44
V_{oc}	**(V)**	21.6	18.74	13.24
I_{sc}	**(A)**	3.2	2.24	30
FF	**(%)**	72.34	55	23.97

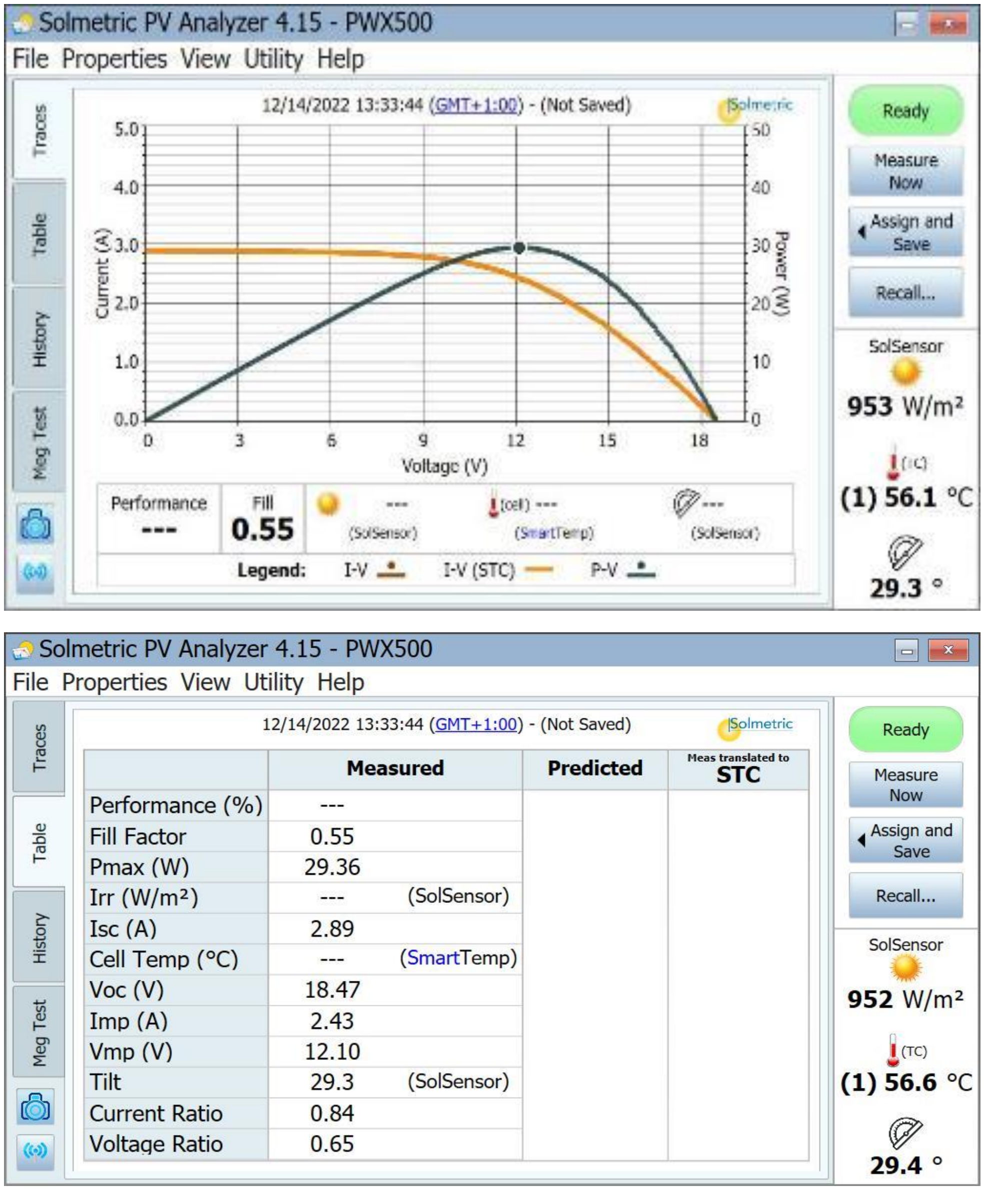


Fig. 3.4 Solar irradiation effect: Solmetric PV Analyzer Characterization of polycrystalline PV module

- **Monocrystalline PV panel**

Tab 3.2 Electrical parameters and degradation rates of tested monocrystalline PV module.

Electrical parameters		STC	Measured	Degradation rate %
P_{max}	(W)	50	25.05	49.9
V_{mpp}	(V)	17.5	13.44	23.2
I_{mpp}	(A)	2.9	2.19	24.48
V_{oc}	(V)	21.6	19.57	9.39
I_{sc}	(A)	3.18	2.59	18.55
FF	(%)	72	58	19.44

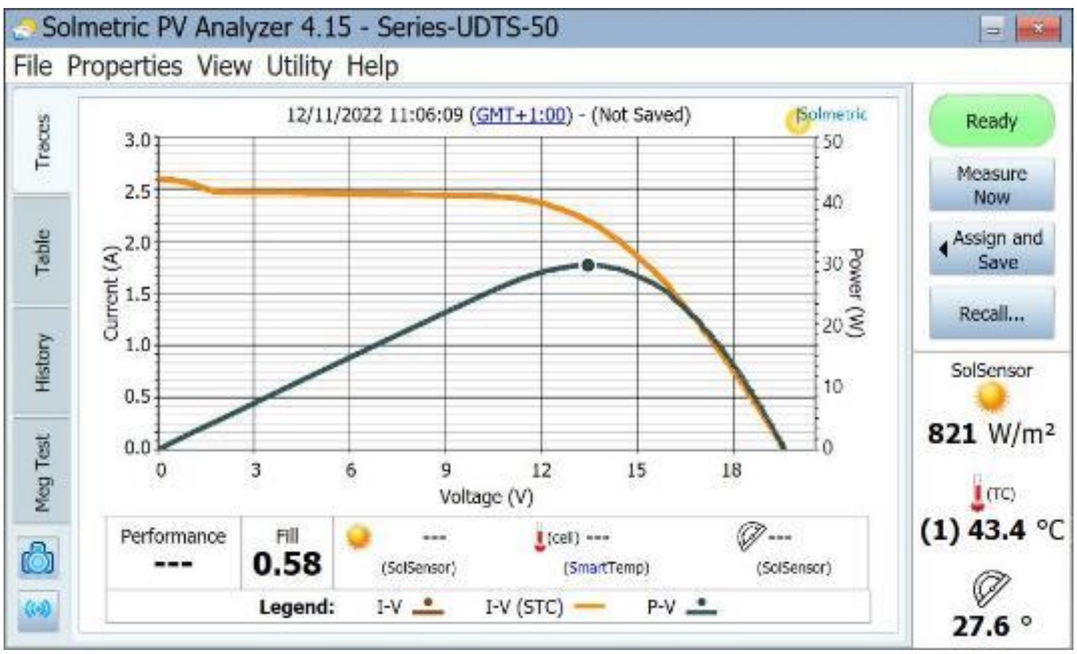


Fig. 3.5 Solar irradiation effect: Solmetric PV Analyzer Characterization of monocrystalline PV module

Fig. 3.6 Bus bar yellowing of polycrystalline PV module.

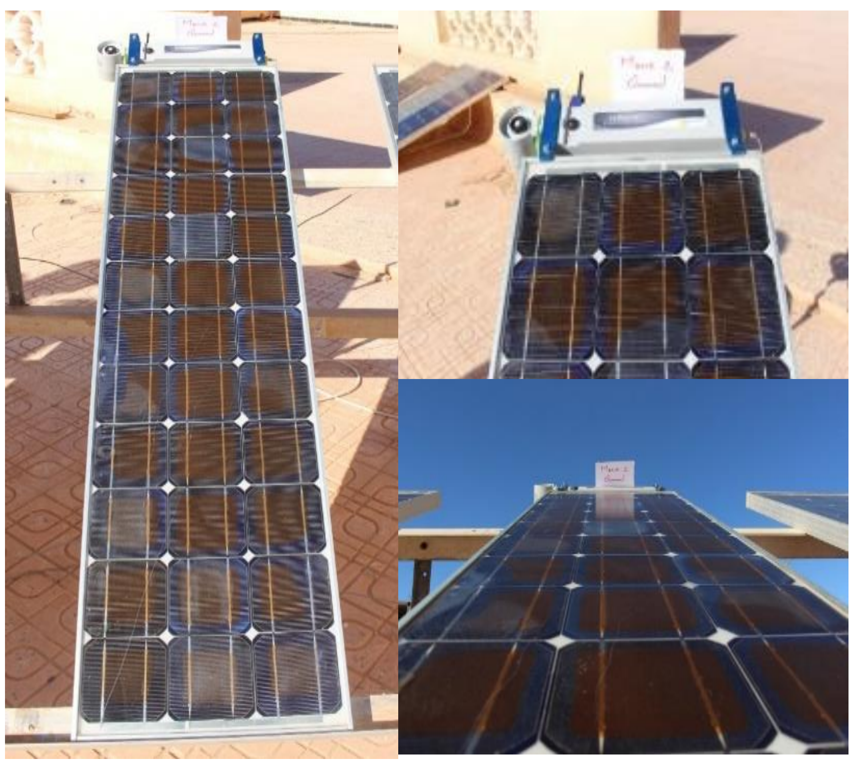


Fig. 3.7 EVA Browning discoloration of monocrystalline PV module.

3.5 Review of temperature influencing the PV panel performance

In PV panels/ systems, ambient temperature plays a crucial role in the photovoltaic conversion process. Temperature is considered an environmental stress factor that has a significant impact on the generated power and the electric performance. The most significant impact is often observed in voltage, where temperatures and voltage are inversely related, see Figure 3.8 [106].

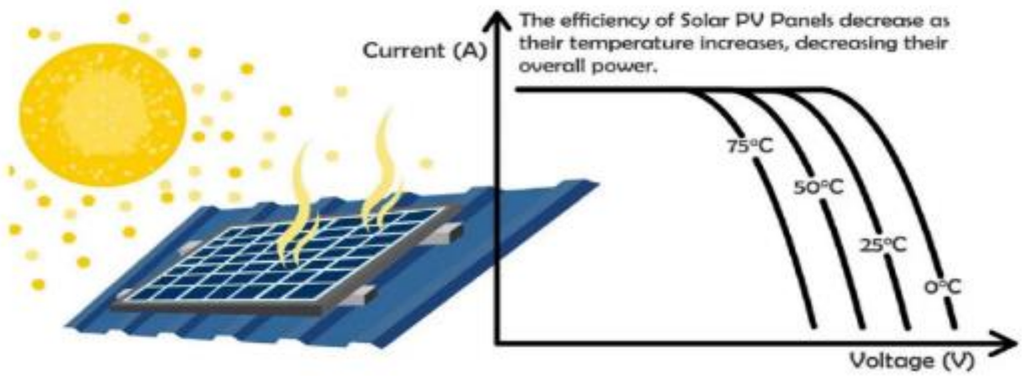


Fig.3.8 Effect of module temperature [106].

3.5.1 Ambient temperature

Regarding the specific climatic characterization of the region, Figures 3.9 and 3.10 show the annual ambient temperature and the minimum, maximum, and monthly average ambient temperatures presenting for four (4) seasons, respectively. It can be observed that the region is extremely hot almost all the year, particularly during hot seasons, where ambient temperatures reach their highest values, ranging from 45 °C and over to 50 °C. By contrast, the region exhibits low ambient temperatures during cold seasons, ranging between 5 °C and 14 °C. Based on the ambient temperature data analysis, the region presents a drastic seasonal temperature range (extremely hot and cold).

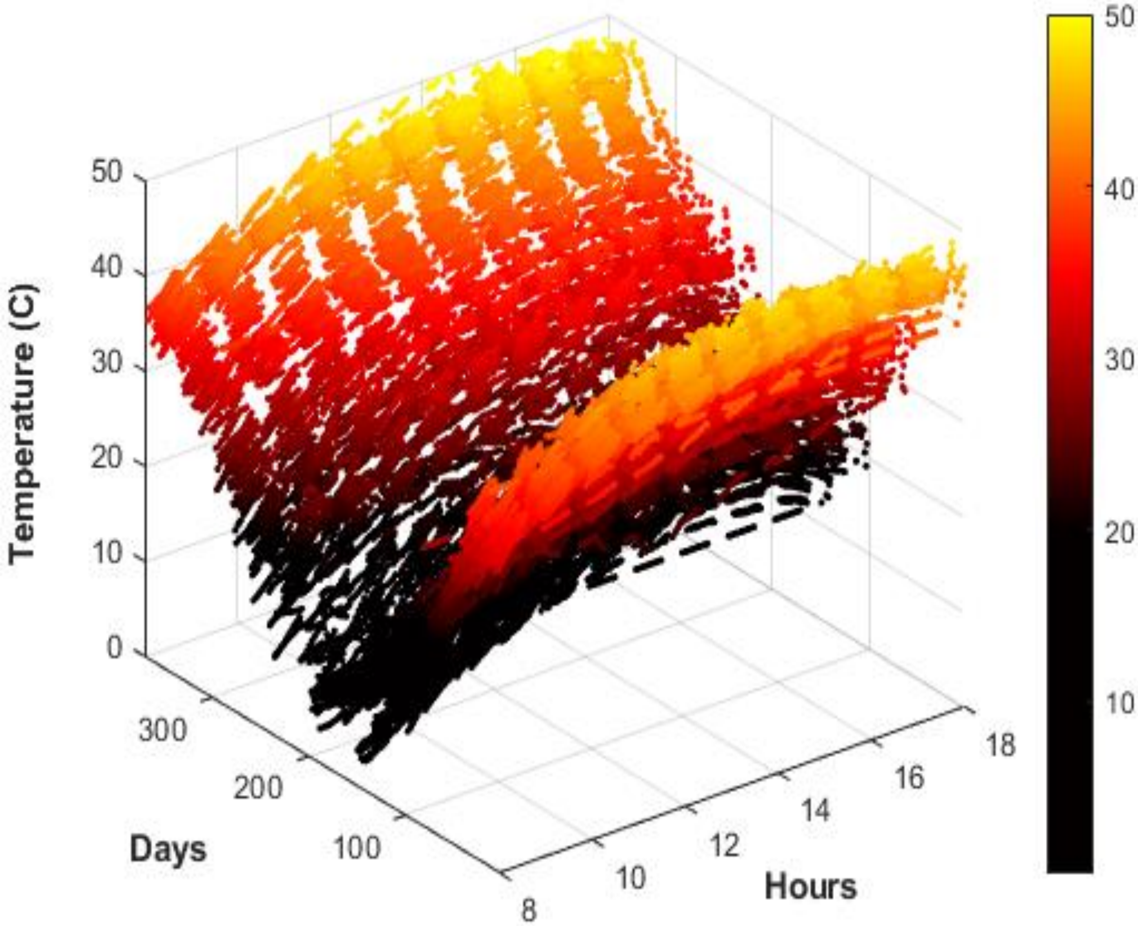


Fig.3.9 Annual ambient temperature .

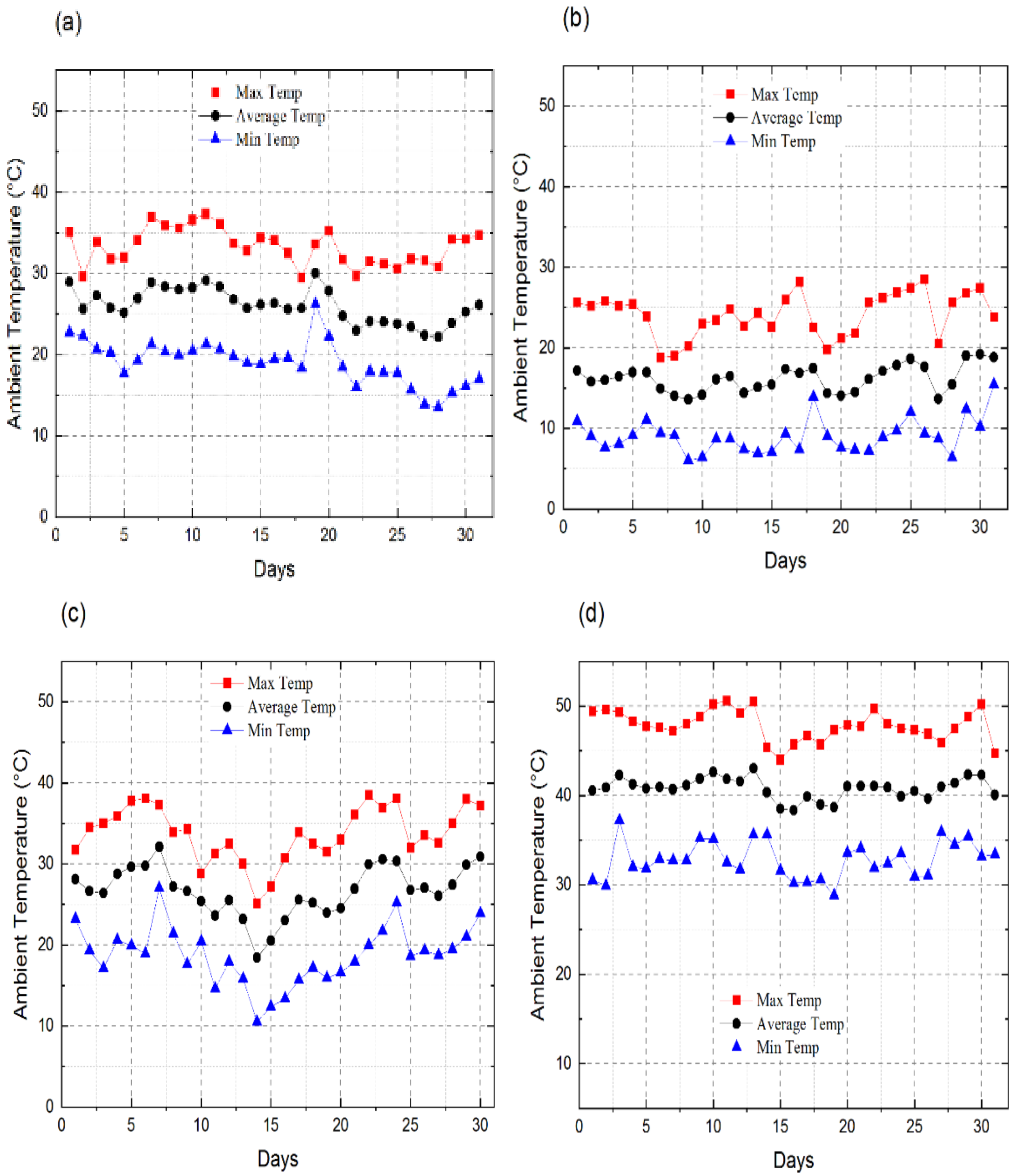
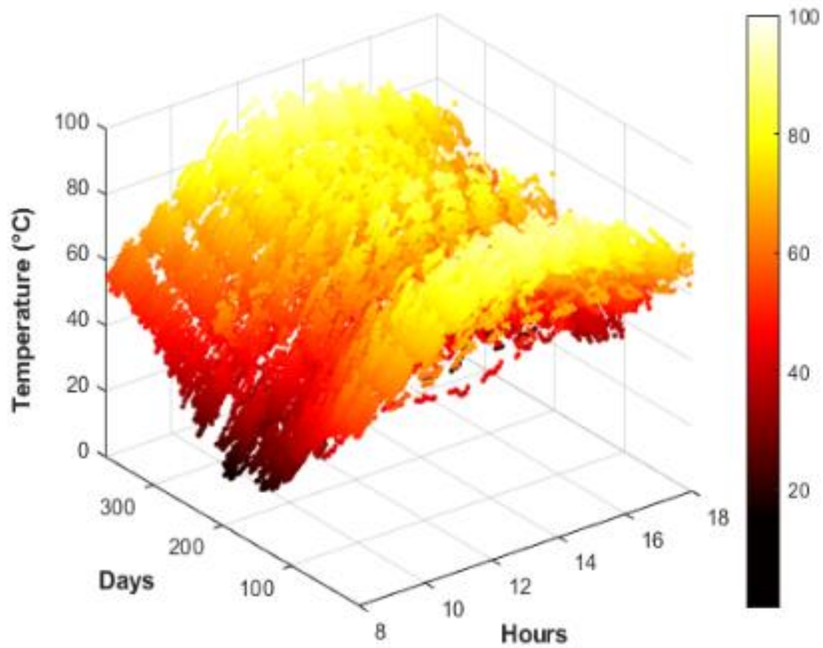
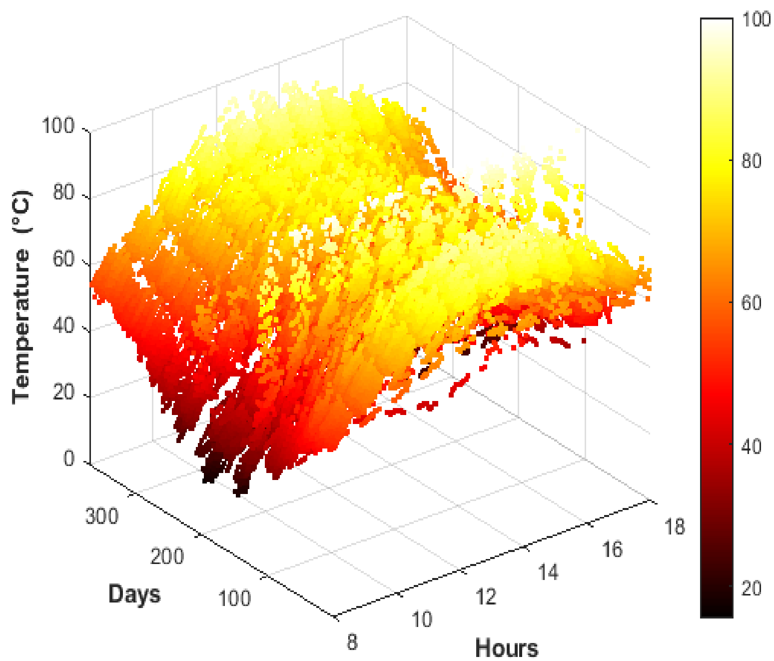


Fig.3.10 Ambient temperature: (a) October, (b) January, (c) April, (d) July

3.5.2 Impact of high ambient temperature accompanied by solar irradiation



(a). Module's 1 temperature



(b). Module's 2 temperature

Fig.3.11 Module's temperature of tested panels

Under field conditions, the ambient temperature and the incoming solar irradiance directly influence the temperature of a solar cell. Therefore, this study evaluates the temperature of solar cells using the Faiman model, designed to assess cell temperature under operating conditions expressed by the following equation 16 [108]:

$$T_{Cell} = T_{amb} + \frac{NOCT - 20}{800} \times G \qquad (16)$$

Where:

T_{Cell}: Panel's temperature (°C).

T_{amb}: Ambient temperature (°C).

NOCT: Nominal Operating Cell Temperature (G: 800w/m², Ambient temperature 20°C).

G: Solar irradiation (W/m²).

The impact of module temperature on electrical performance in photovoltaic (PV) modules has been investigated in this part of study. At a high level of solar irradiation (780 w/m²) and (865 W/m²), module temperature reaches up to 50°C. As presented in tables 3.3 and 3.4, both tested panels show a significant degradation in electrical performance highlighted by a decrease in Voc, Isc, and FF resulting in a big drop in output power. In this case study, PV panels exhibit a significant increase in series resistance. This increase may result from poor thermal connections, leading to thermo-fatigue defects.

Tab 3.3 Effect of module's temperature on the electrical parameters of tested polycrystalline PV module.

Electrical parameters		**STC**	**Measured**	**Degradation rate %**
P_{max}	**(W)**	50	23.08	53.84
V_{mpp}	**(V)**	17.2	13.11	25.08
I_{mpp}	**(A)**	2.9	1.76	39.31
V_{oc}	**(V)**	21.6	18.59	13.93
I_{sc}	**(A)**	3.2	1.99	37.73
FF	**(%)**	72.34	62	14.29

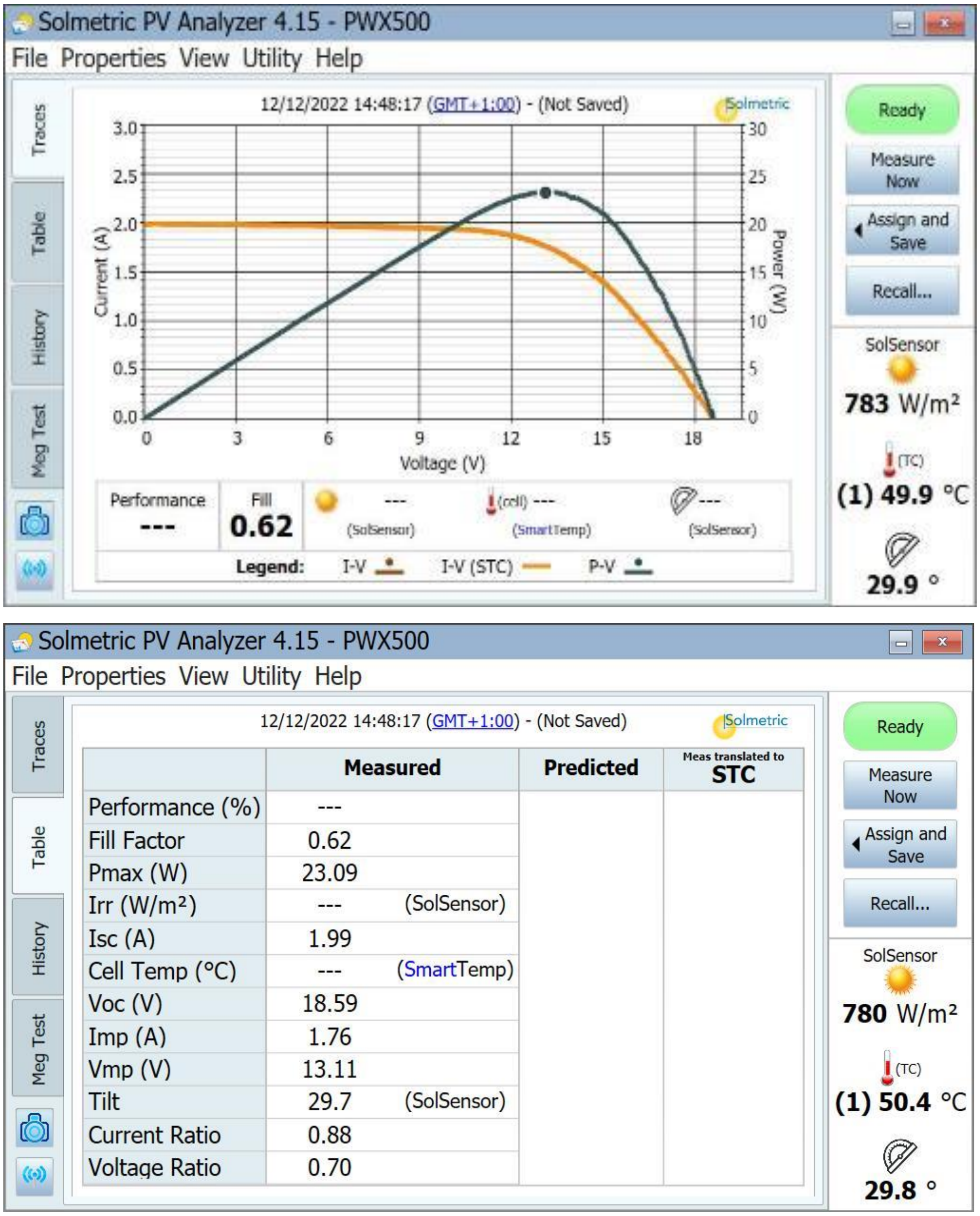


Fig.3.12 Module's temperature effects: Solmetric PV Analyzer characterization for Polycrystalline PV module

Tab 3.4 Effect of module's temperature on the electrical parameters of tested monocrystalline PV module

Electrical parameters		STC	Measured	Degradation rate %
P_{max}	(W)	50	27.54	44.92
V_{mpp}	(V)	17.5	12.87	26.45
I_{mpp}	(A)	2.9	2.13	26.55
V_{oc}	(V)	21.6	19.35	10.41
I_{sc}	(A)	3.18	2.55	19.81
FF	(%)	72	58	19.44

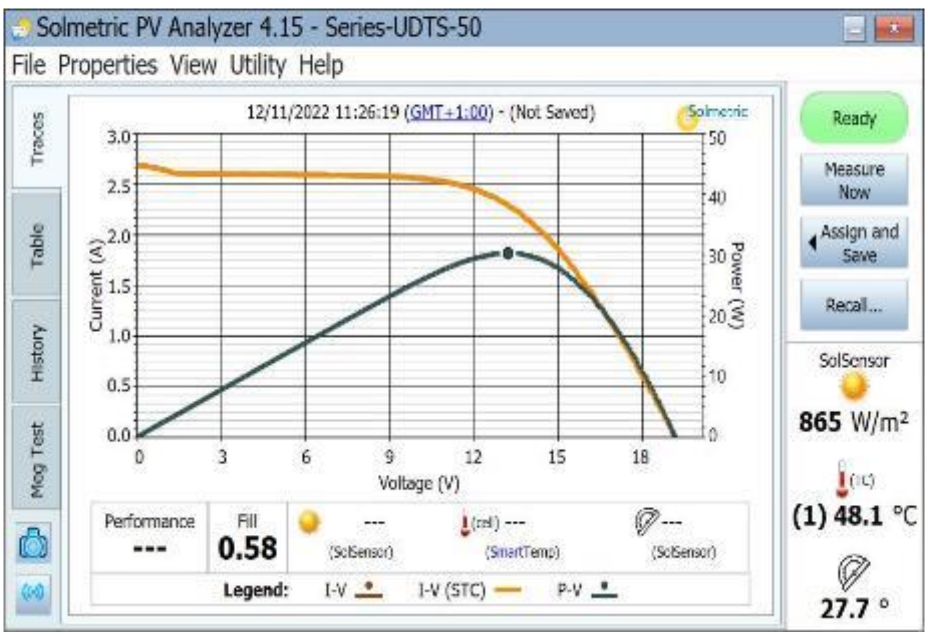


Fig.3.13 Module's temperature effects: Solmetric PV Analyzer characterization for monocrystalline PV module

From Figures 3.14 and 3.15, visual inspection revealed that panels suffer high discoloration degrees manifest in browning and dark browning discoloration. As reported in the literature, EVA discoloration is the most common visual PV panel defect [93], [105], [109]**.** According to [94], [110]**,** EVA discolorations are primarily attributed to changes in the polymer's chemical structure when subjected to UV radiation and water at temperatures exceeding 50°C. Therefore, The EVA discoloration process manifests initially in yellow (light discoloration) and progressively changes to darker shades of brown (dark discoloration). On the other hand, another visual defect was observed on tested PV panels characterized by discoloration of fingers and/or the bus bars. [93], [109], [110] claimed that the discoloration of metallization occurs when the EVA is exposed to UV rays accompanied by high temperatures.

Under harsh conditions of the desert, high ambient temperature accompanied by high solar irradiation increases significantly the modules' temperature, reaching up to 90 °C, as depicted in Figure 3.11. Consequently, increasing modules' temperature accompanied by high UV doses is the main source of degradation of encapsulant manifesting by color changes (browning/ dark browning), these changes serve as visible indicators of physical defects in the material.

Moreover, it could be identified the nature of these defects through the analysis of the I-V curves of PV panels. Figures 3.12 and 3.13 present I-V curves after characterization using a Solmetric PV Analyzer. In addition, the characterized data was treated and converted to STC, to assess the degradation between the measured and manufacturers' I-V curves.

Based on the translated measurements in STC as detailed in Tables 3.3 and 3.4, both panels appear significant degradation in Isc followed by Voc. Specifically, the polycrystalline panel shows a mean degradation rate of Isc exceeding 3%/year, while the Monocrystalline panel shows a rate of 1.8%/year. For Voc, the mean degradation rates are 1.36%/year for the polycrystalline panel and 0.96%/ year for the Monocrystalline panel and hence results in a lowering of the I-V curve.

These degradation rates in electrical parameters result in a significant decrease in output power, with a degradation rate reaching up to 4% /year for both panels. , which is far from the degradation rate of less than 1% per year. Therefore, this study is in agreement with studies performed in the Desert regions [11], [92], [97].

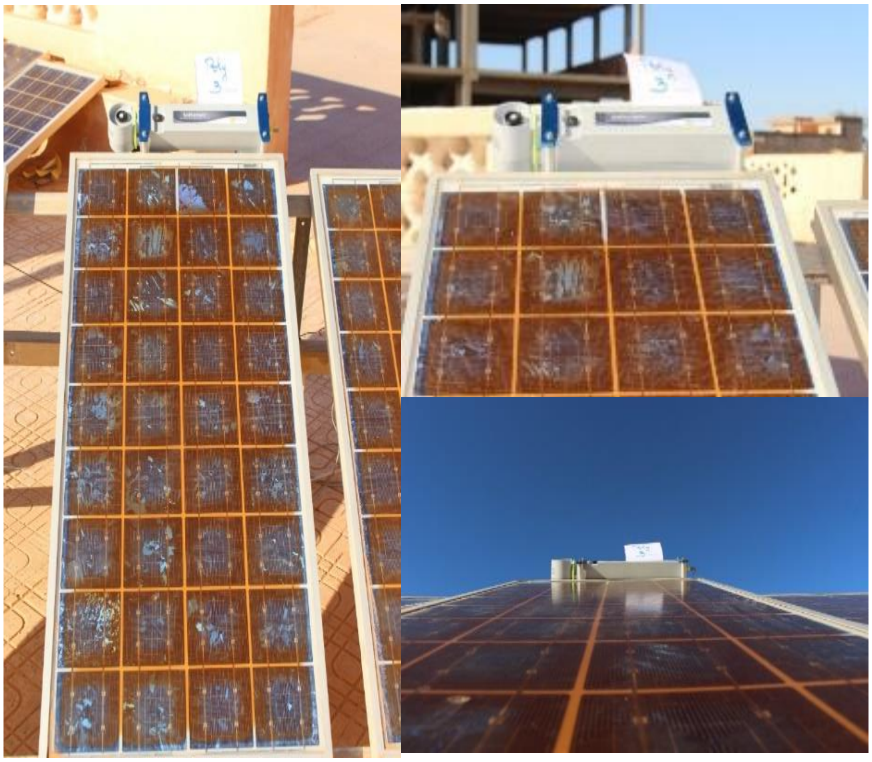


Fig.3.14 Fingers and bus bars discoloration of polycrystalline PV module

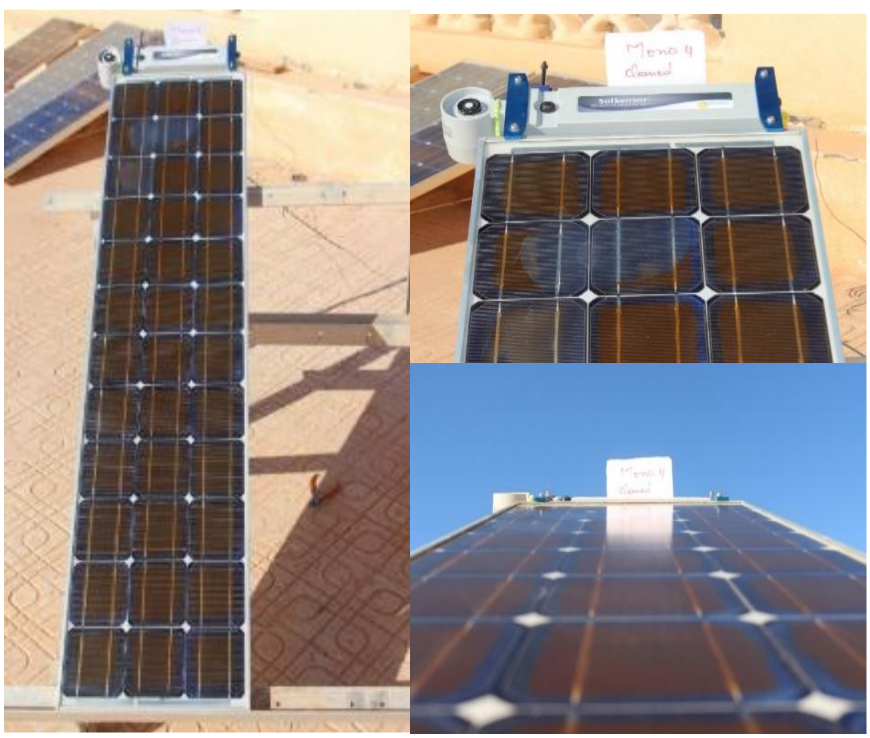


Fig.3.15 EVA Browning / dark browning discoloration of monocrystalline PV module

Studied degradation modes reveal a strong relationship between PV panel degradation and the harsh climate, where encapsulant discoloration was predominant in hot and dry regions because of high temperatures. These high temperatures significantly contribute to the acceleration of encapsulant discoloration in such environments. In the experimental study, it was found that increasing panel temperature reduced all electrical parameters, including open circuit voltage, fill factor, efficiency, and maximum power, while short circuit current significantly increased.

3.6 Review on dust accumulation influencing PV panel performance

Dust accumulation on the surface of PV panels is one of the major challenges, particularly in arid and desert areas. Dust accumulation is characterized by a thin layer that can scatter or absorb light energy by decreasing the transmissivity of the glass cover, causing shading and therefore leading to a significant reduction in the amount of solar irradiation reaching the PV panel surfaces' [5], [111]. Moreover, climatic conditions in arid / desert areas such as wind velocity, low rainfall, and PV module orientation play a significant role in dust deposition, contributing to soiling over time [112], [113]. This accumulation directly affects the performance of PV panels, leading to a decrease in output power [114]. Besides the degradation in output power, the short-circuit current is highly affected by dust accumulation compared to the less sensitivity of open-circuit voltage Voc. Several studies have been carried out in desert regions, and particularly in the Algerian desert aiming to determine the impact of dust accumulation on the performance of PV panels. Findings revealed that over an extended exposure duration, dust accumulation can lead to a reduction of up to 50% in PV output power[101], [111], [115], [116].

3.6.1 Impact of dust deposition on the surface of PV modules

To investigate the effect of dust accumulation on the performance of PV panels. Tests were conducted in a desert area using two panels Mono and polycrystalline**.** Through the visual inspection technique on the tested PV panels, it is observed that the dust covers the PV panel surface, as depicted in Figures 3.16 and 3.17.

Tables 3.5 and 3.6 present respectively, the electrical specifications of both tested PV panels and data that have been taken out and translated to standard test conditions (STC) after characterization.

Tab 3.5 Effect of dust deposition on the electrical parameters of tested polycrystalline PV module

Electrical parameters		**STC**	**Measured**	**Degradation rate %**
$\mathbf{P_{max}}$	**(W)**	50	20	60
$\mathbf{V_{mpp}}$	**(V)**	17.2	13.39	23.48
$\mathbf{I_{mpp}}$	**(A)**	2.9	1.49	48.62
$\mathbf{V_{oc}}$	**(V)**	21.6	18.56	14.07
$\mathbf{I_{sc}}$	**(A)**	3.2	1.72	45.91

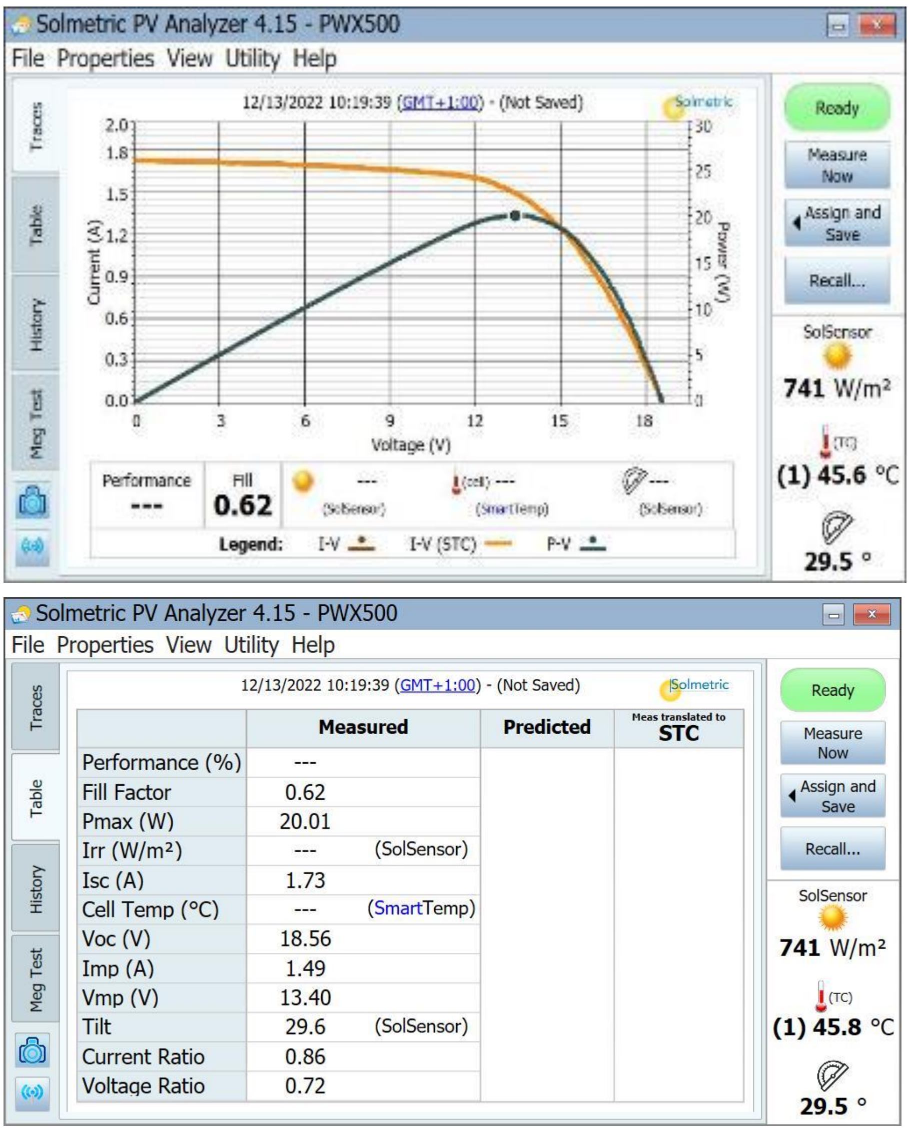


Fig.3.16 Dust deposition effect: Solmetric PV Analyzer characterization for polycrystalline PV module

Tab 3.6 Effect of dust deposition on the electrical parameters of tested polycrystalline PV module.

Electrical parameters		STC	Measured	Degradation rate %
P_{max}	(W)	50	28.55	42.9
V_{mpp}	(V)	17.5	13.48	22.97
I_{mpp}	(A)	2.9	2.11	27.24
V_{oc}	(V)	21.6	19.23	10.97
I_{sc}	(A)	3.18	2.45	22.95
FF	(%)	72	60	16.66

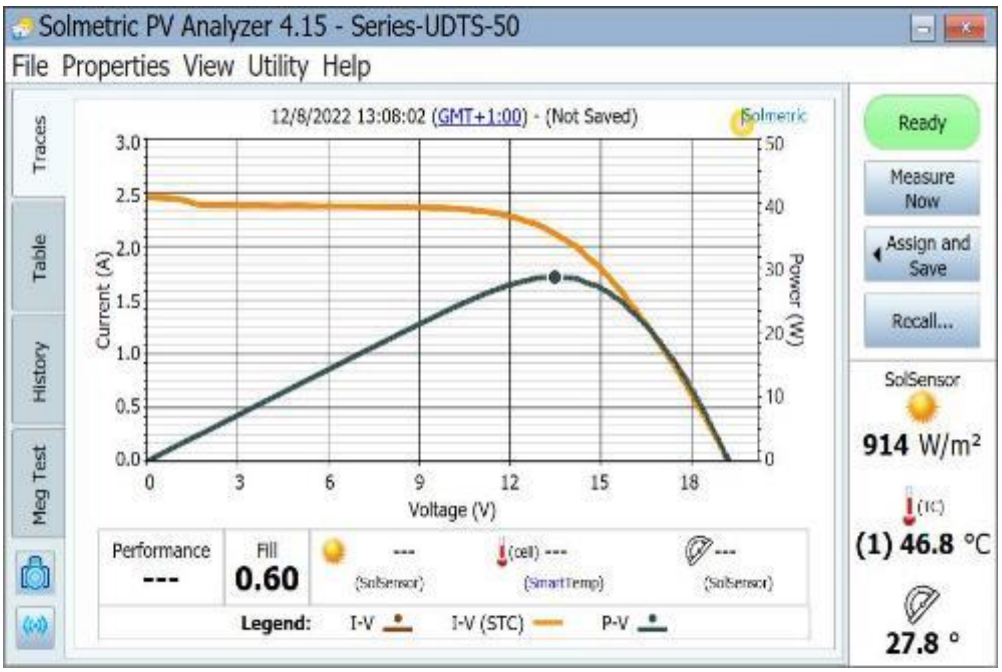


Fig.3.17: Dust deposition effect: Solmetric PV Analyzer characterization for monocrystalline PV module

The results showed losses in output power accompanied by a significant decrease in short-circuit current, while the Voc appears less sensitive to the dust effect. Under outdoor conditions, PV panels are fixed at a tilt angle of 28° oriented to the south and at solar irradiation above 800 W/m².

Fig.3.18 Dust deposition on tested polycrystalline PV module

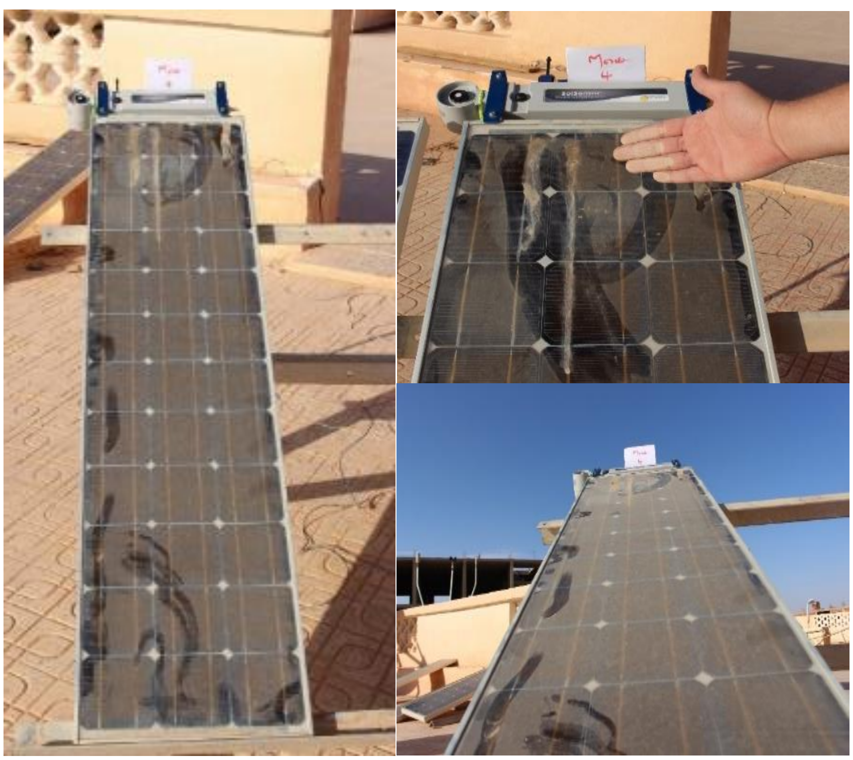


Fig.3.19 Dust deposition on tested monocrystalline PV module

The polycrystalline panel (see Figure 3.18) shows an important loss in output power estimated by 30 Wc, while Monocrystalline experiences 22 Wc (see Figure 3.19). On the other hand, results showed that short-circuit current for both panels decreased by 1.46 A, and 1.25 A, respectively, presenting mean degradation rates of 4%/year and 2%/year, while the degradation rates in the output power are considered at 5% and 4% for polycrystalline and monocrystalline, respectively. Additionally, Figs. 22 and 23 revealed a decline in both the I-V and P-V characteristics of the anels, particularly in short circuit current Isc, indicating the strong correlation between solar irradiation, output power, and short circuit current.

3.7 Conclusion

Desert climates are environments that stress the modules far stronger than other environments, and therefore failure of PV panels appears within the first few years of the operation.

The chapter presented the climatic factors contributing to the accelerated degradation mechanism and failure of standard panels in Algeria's desert, including solar irradiance, ambient temperatures, and dust deposition. It also identified the most frequent degradation and failure modes that occur generically in this region.

In conclusion, according to the environmental characteristics, it is imperative to choose PV panels that will be adequate for such conditions for large-scale deployments, as well as electricity generation by photovoltaic power sources in desert regions, which will be taken as a case study for the next chapter.

CHAPTER IV

Monitoring, and performance analysis of 6MW grid-connected in desert: Case study

4.1 Introduction

Due to the clear absence of long-term evaluations of large-scale PV systems installed in desert regions, the chapter analyses the impact of climate conditions on the performance of a 6-MW grid-connected PV power plant situated in the southwest of Algeria, Adrar. An investigation and assessment study were conducted on the impact of solar irradiation and ambient temperature on the PV station's performance over a five-consecutive-year period of monitoring. The main objective of this chapter is to carry out in-depth analyses and look at the PV plant's operation to make recommendations for potential future improvements in efficiency and the expansion of clean energy in southern Algeria.

4.2 Description of location study

The Zaouiet Kounta photovoltaic power plant is located 2 km north of Zaouiet Kounta, Adrar province, approximately 1400 km south-west of Algiers, at 27.52° North latitude and 17° West longitude, with a 279-meter altitude. The region located in the extreme south of Algeria is characterized by extreme and harsh climatic conditions (Bwh class by the Köppen-Geiger system) [117], especially in the summer, and a sunny clear sky almost all the year, which offers better opportunities for solar installations attributed to its topography, as shown in Figures 4.1 and 4.2 [68], [69], [118]. The PV plant in Zaouiet Kounta, Adrar is a part of Algeria's national program for using renewable energies. The program was adopted in 2011 and aims to install around 22,000 megawatts of renewable energy across the country by 2030 [29]. The project was established on 12 hectares, within the framework of cooperation between China Hydropower Engineering Consulting Group, Sinohydro, Yingli Green Energy, and SKTM. The PV station was put into service in January 2016, considering that it is affiliated with and managed by the Electricity & Renewable Energy Company (SKTM).

Fig. 4.1 Zaouiet Kounta 6MW PV power plant

4.3 Description of the 6 MW photovoltaic power plant

The photovoltaic power plant installed near the 220/30 KV injector (GRTE), consists of 24552 Polycrystalline PV panels. All installed panels are identically manufactured by YINGLI SOLAR (Figure 4.3), which were mounted on the ground with a tilt angle of 28° facing south [69]. The photovoltaic station is divided into 06 sub-fields, each sub-field produces 1 MWp, and has 93 Matrices, within each matrice 44 panels are divided into 2 strings, and each string consists of 22 panels connected in series. For every eight strings (4 matrices), a junction box is employed (Figure 4.4). Additionally, each 3 junction boxes are connected to form a parallel box (Figure 4.5), and 4 parallel boxes are connected to a general box located in a shelter (Figure 4.6). A shelter contains 2 general boxes and 2 inverters type **SUNGROW** (Figure 4.9). The general box is connected to the inverter (DC / AC), which is in turn connected to the transformer (315 V / 30 kV). The transformer is connected to the ports responsible for injecting power into the electrical grid via a busbar. Furthermore, solar radiation and ambient temperature are monitored, and real-time data is collected every 15 minutes. In addition, the characteristics of the PV module and the inverter are presented in Tables (4.1), and (4.4) respectively.

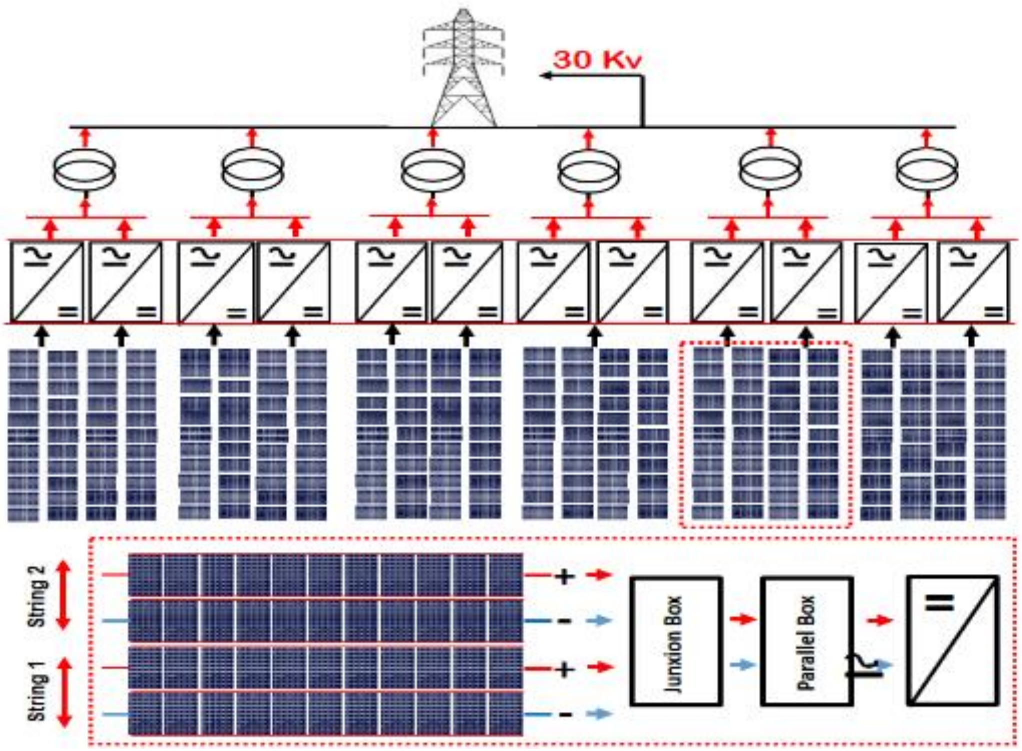


Fig. 4.2 Zaouiet Kounta 6MW PV power plant Schematic diagram

4.4 Components and characteristics of the Zaouiet Kounta PV plant

4.4.1 Photovoltaic PV panel

Yingli Solar is an integrated manufacturer of solar photovoltaic modules. The Yingli Solar PV panel comprises 60 polycrystalline silicon cells connected in series, covering 1.98 m² of the panel surfaces, with a maximum power of 245 Wc. Further panels' specifications are mentioned in **Table 4.1**.

Table 4.1 Photovoltaic module specifications at standard test conditions STC (1000 W/m² and 25°C).

Parameters	Specification
Manufacturer	Yingli
Cell type	Polycrystalline
Number of cells	60

Electrical Specification

Maximum power	Pmax	(W)	245
Maximum power voltage	Vmax	(V)	29.6
Maximum power current	Imp	(A)	8.28
Open circuit voltage	Voc	(V)	37.5
Short circuit current	Isc	(A)	8.38
Module efficiency	η	(%)	15.1
Maximum system voltage		(V)	1000
Temperature coefficient of P_{max}	γ_{Pmax}	(%/°C)	-0.42
Temperature coefficient of Isc	β_{Isc}	(%/°C)	0.05
Temperature coefficient of Voc	α_{Voc}	(%/°C)	-0.32

Fig 4.3 YINGLI SOLAR PV panel specification

4.4.2 Connections box

4.4.2.1 Junction boxes

Figure 4.4 presents the junction box model SUNGROW, model PVS-8M, further technical characteristics mentioned in **Table 4.2**

The junction boxes must have ~8 inputs (both polarities) 4 mm² and two outputs up to 70mm², an earth connection with a minimum cross-section of 16mm² including fuse protection on all inputs (size 10×38 and type gR), an output switch-disconnector, a class II lightning arrester, and a string monitor.

Table 4.2 Technical characteristics of SUNGROW junction box.

Manufacturer	SUNGROW
Model	PVS-8M
Maximum voltage	1000 V
Maximum No° DC input	8 A
Fusible	15 A
Max output Current	125 A
Max output DC Current	106 A
IP protection	IP 65
Ambient temperature	-25°C to + 60°C

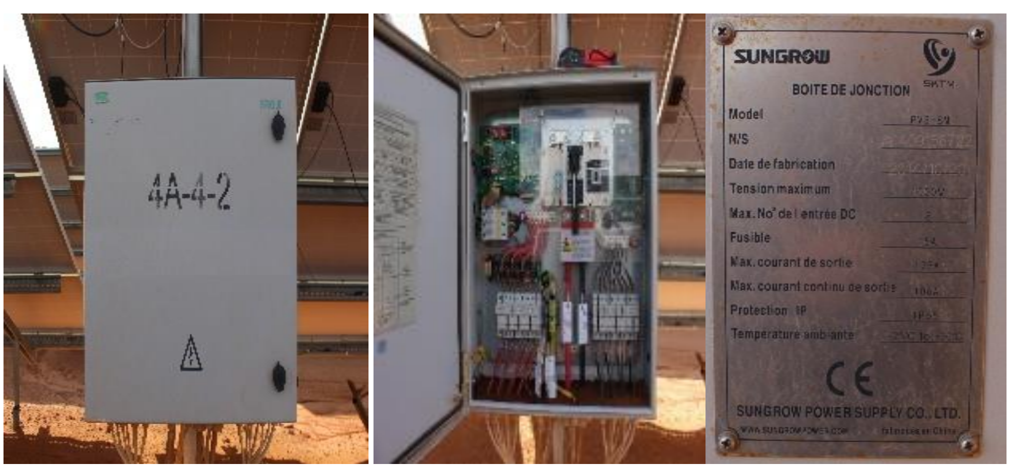


Fig. 4.4 Junction box

4.4.2.2 Parallel Box

Figure 4.5 shows the parallel box model SUNGROW, model PMD-125K. Additional technical features are detailed in **Table 4.3**.

Table 4.3 Technical characteristics of SUNGROW parallel box.

Manufacturer	**SUNGROW**
Model	PMD-D125K
Nominal power	125 KW
Maximum voltage DC	1000 V
Max. N° input DC	4
IP protection	IP 65
Ambient temperature	-25°C to + 60°C

The parallel boxes are designed to incorporate the following elements: Four inputs at 70 mm² (both polarities) and one output (both polarities) up to 240 mm². The inputs consist of a fuse switch and the output of a switch-disconnector, according to a single-line diagram. As presented in the connection diagram of parallel box (See Figure 4.6).

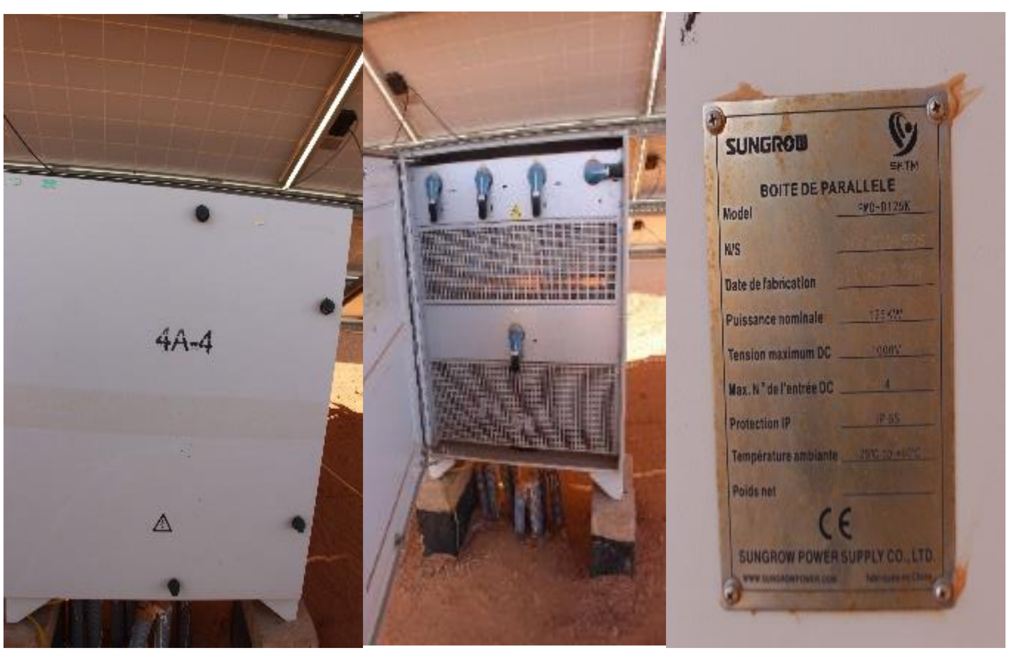


Fig. 4.5 Parallel box.

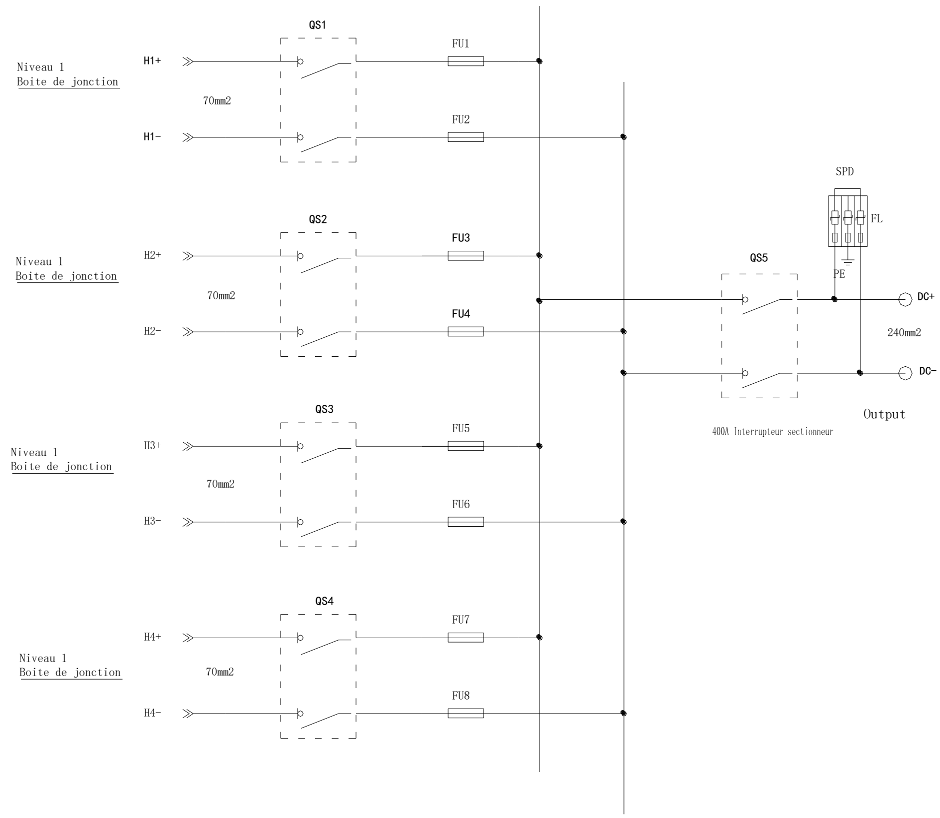


Fig. 4.6 Connection diagram of parallel box.

4.4.2.3 General Box

Figure 4.7 presents the general box. Additionally, Table 4.4 provides the technical characteristics of the SUNGROW General Box model PMD-D500K.

Table 4.4 Technical characteristics of SUNGROW general box

Manufacturer	SUNGROW
Model	PMD-D500K
Nominal power	500 KW
Maximum voltage DC	1000 V
Max. N° input DC	4
IP protection	IP 21
Ambient temperature	-25°C to + 60°C
Weight	226 Kg

Fig.4.7 General Box

These boxes must have four inputs (both polarities) and four outputs (both polarities) up to 240 mm². They will consist of a switch-disconnector. As shown in Connection diagram of general box).

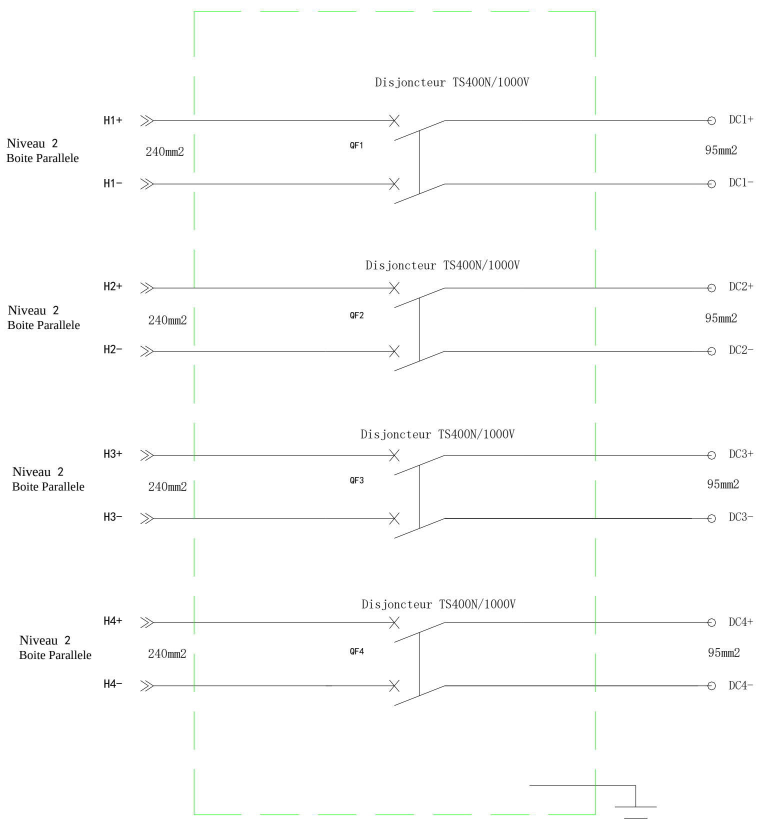


Fig. 4.8 Connection diagram of general box

4.4.2.4 Inverter

The electricity generated by the photovoltaic panels is carried to junction boxes via cables along the panel supports. The junction boxes are then connected to inverters via underground cables. Figure 4.9 presents SUNGROW solar inverter model SG500MX, furthermore, Table 4.5 provides additional technical characteristics of the SUNGROW inverter (Shelter).

Fig.4.9 SUNGROW Inverter (Shelter)

Table 4.5 Technical characteristics of SUNGROW Inverter (Shelter)

Manufacturer	**SUNGROW**
Model	SG500MX
Input DC	
Maximum voltage	1000 V
Isc	1344 A
Voltage VMPP min	500 V
Voltage VMPP max	850 V
Maximum input current	1120 A
Surge categories	II

Output AC	
Nominal output power	500 Kw
Nominal output voltage	3 ~ 315 V
Nominal output frequency	50 Hz
Max output current	1008 A
Power factor	[-0.9- 0.9]
Surge categories	III
Class protection	I
IP protection	IP 21

4.4.2. Transformer

Generally, transformators raise the current voltage at the output of the inverters to reach the level required by the electrical network. The electricity passes into the plant's collector network at the outlet, made up of underground cables. Figure 4.10, and Table 4.6 present SUNTEN transformator type ZBW10A-1250, followed by technical characteristics.

Fig. 4.10 SUNTEN transformator

Table 4.6 Technical characteristics of SUNTEN transformator

Manufacturer	SUNTEN
Model	ZBW10A-1250/30
Nominal capacity	1250 KVA
Product code	Z140237-02155
Nominal voltage	30/0.315
Nominal frequency	50 Hz
Weight	8300 Kg
Dimensions	4700×2438×2896 mm

4.4.3 Weather station

The automatic weather station serves as weather observation equipment that can automatically acquire, process, record, and transmit different weather elements according to specified requirements, to improve the quality and efficiency of observation.

The NARI automatic weather station at the Zaouiet Kounta PV plant, as illustrated in Figures 4.11 and 4.12, is equipped to measure various meteorological variables such as temperature, humidity, irradiance, atmospheric pressure, and wind speed. Additionally, more technical specifications of the weather station are summarized in [118].

Fig 4.11 NARI weather station equipment

Fig 4.12 NARI weather station at Zaouiet Kounta PV station

4.4.4 Monitoring and control system

The SCADA and OPC SERVER system provided by NARI Group Corporation is a monitoring platform for power plant (**See Figure 4.13)**. It plays a central role in the supervision, operation, and management of power plants by centralizing detected data. This data is then processed and analyzed to optimize production, in particular by detecting possible anomalies. Simultaneously, appropriate control commands are transmitted from the centralized control room. At the same time, the monitoring system transmits relevant data to the higher-level electric power dispatch center. This center receives and executes orders issued by the energy dispatching center, thus ensuring effective coordination of operations.

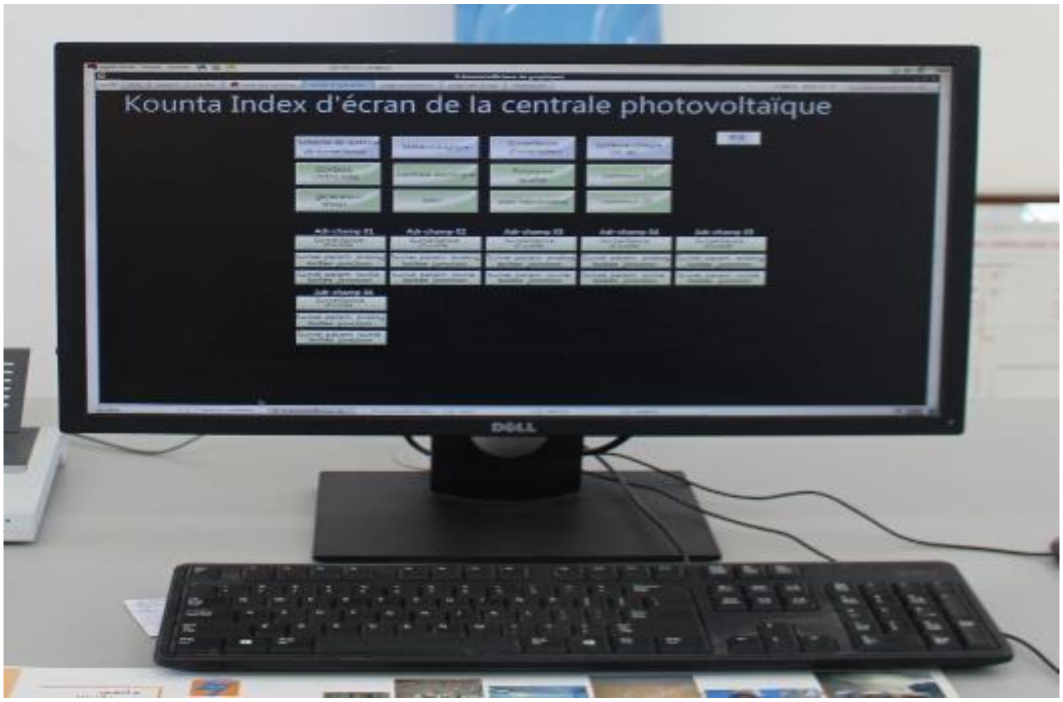


Fig 4.13 Principle control interface (SCADA)

4.5 Environmental factors affecting the performance of PV power plants in desert

In this part, the overall performance of the PV system is evaluated by presenting the weather data for the studied region. In addition, the effect of ambient temperature accompanied by solar irradiation on the system's performance was investigated during a monitoring period.

4.5.1 Monitoring of climatic data in Desert region

In the arid and desert region of Adrar, Algeria. The weather conditions of Zaouiet Kounta PV power plant (SKTM, Zaouiet Kounta) were recorded using a SCADA NC2000 software monitoring system and the automatic weather station NARI. Over a continuous period of five years, from 2017 to 2021, measurements were collected every 15 minutes from the weather station. The measurement data for meteorological parameters include solar irradiation, ambient temperature, wind speed, humidity, and atmospheric pressure. This monitoring period develops a database containing information on climatic conditions, providing clearer insights into the climate of the region and providing a concrete set of answers to the questions that have to be addressed to understand the environmental factors influencing the performance of the PV power plant in the desert regions.

4.5.1.1 Monitoring of solar irradiation

Based on the collected data from the NARI automatic weather station for solar irradiation for five years of monitoring. The measurement data from the years 2017 to 2021 are illustrated in figure 4.14, respectively**.**

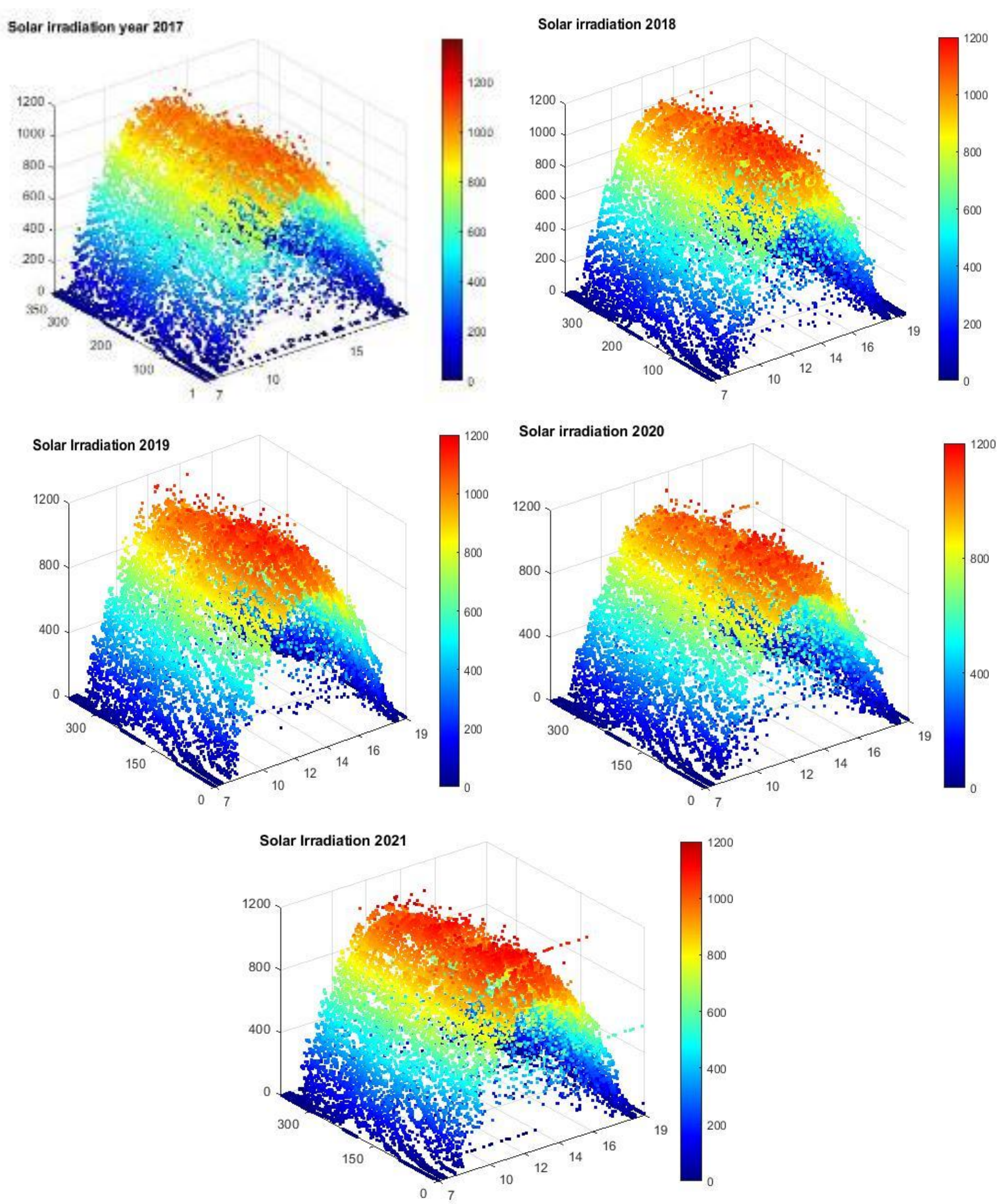


Fig 4.14 Five years monitoring of solar irradiation

The overall view of Figure 4.14, it is clear that the considered region is blessed with abundant solar energy throughout the year and features clear sky conditions most of the year. Through the database containing solar irradiation, it can analyze the amount of solar irradiation day by day and year by year during the monitoring period.

Solar irradiation exhibits significant variations corresponding to the seasons. Over the year 2017, solar irradiation varies across different seasons, with winter and autumn seasons ranging from 600 W/m² to 900 W/m². On clear days in these seasons, it recorded the highest values reaching 1080 W/m². As well, the year 2018 recorded a range from 600 W/m² to 800 W/m², with a peak value at clear days considered by 1002 W/m². Besides that, in the year 2019, it was observed that solar irradiation measurements range from 500 W/m² to 800 W/m², reaching 981 W/m² as the highest capture during clear days. During the year 2020 and 2021 in this period of seasons, it is noted that solar irradiation measurements range from 700W/m² to 900 W/m², and 600 W/m² to 800 W/m², respectively. Furthermore, the highest capture during clear days reached 1012 W/m², and 928 W/m². By contrast, the spring and summer seasons experienced high availability of solar irradiation with a significant number of clear sky days. The solar irradiance recorded during these hot seasons ranged from 800 W/m² to 1200 W/m² throughout all years of monitoring. On clear days, the highest values recorded were 1373 W/m² in July 2017, 1365 W/m² in May 2018, 1297 W/m² in April 2019, 1352 W/m² in August 2020, and 1288 W/m² in July 2021.

The reported data confirms that the studied region is characterized by a large amount of solar irradiation and numerous clear days accompanied by long sunshine duration throughout the year, making it ideal for solar energy generation.

4.5.1.2 Monitoring of ambient temperature

The region, classified in (Bwh) according to the Köppen climate classification, is characterized by hot and dry climatic conditions [119]. Throughout the monitored period, the NARI weather station records ambient temperature (Tamb) at 15-minute intervals using a temperature sensor. Figure 4.15 presents the measurement of ambient temperature from the years 2017 to 2021.

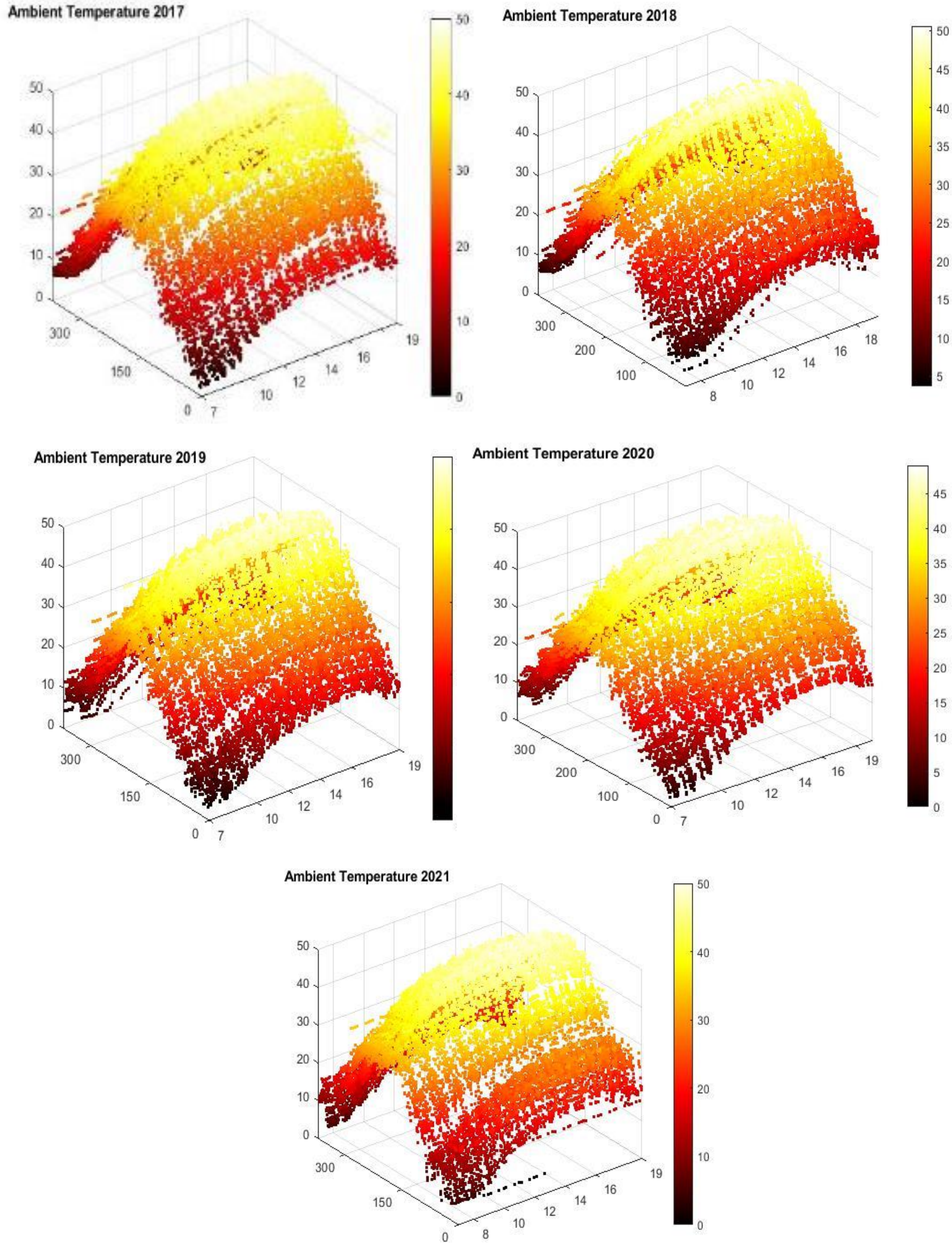


Fig 4.15 Five years monitoring of ambient temperature

The region is characterized by challenging weather conditions, experiencing cold winters and hot summers. As presented in Figure 4.15, During the hot seasons of the monitored period, the ambient temperature reached its highest value of 48°C for the years 2017 and 2018, while through the years 2019, 2020, and 2021, it ranged between 47°C and 49°C. Typically these seasons are almost hot and experience high temperatures ranging from 40°C to 45°C. Over the cold seasons, the ambient temperature decreased, ranging from 14°C to 18°C throughout the years 2017, 2018, and 2019, and for the years 2020 and 2021, it was between 16°C and 20°C.

In some regions, especially desert climates, the temperature variations can be much higher than in other regions. In the studied location, the difference between maximum and minimum recorded temperature (day and night) can range from 10°C to 12°C, during the cold seasons. As well as, in the hot seasons where that can range from 10°C to 18°C.

4.5.1.3 Monitoring of wind speed, humidity, and atmospheric pressure

In arid regions, moisture from evaporation accounts for a small fraction due to the low precipitation levels.

Table 4.6 Five years monitoring of average wind speed, humidity and atmospheric pressure

	Wind speed (m/s)	**Humidity (%)**	**Atmospheric pressure (Hpa)**
Year 2017	10.88	22.92	978.01
Year 2018	4.97	22.86	981.71
Year 2019	5.25	20.62	981.84
Year 2020	5.38	21.58	981.89
Year 2021	5.08	19.23	980.29

As indicated in Table 4.6, the region experienced a low humidity rate ranging from 19% to 23%. Also, the atmospheric pressure has a small change fraction and is stable at 981 Hpa. As well, the wind speed varies from 5 m/s to 10 m/s over the monitoring period.

4.5 Study of the effect of ambient temperature accompanied by solar irradiation on system's performance

The combined effect of high ambient temperatures and high irradiation is a big challenge to the performance of PV systems installed in hot desert. These two factors have a contradictory effect on power generation, where the high ambient temperature causes a reduction in the PV panel output power (Figure 4.16).

Based on the data collected in the field, this investigation aims to understand the performance and degradation aspects of PV panels related to long-term reliability in the desert region by determining the effect of ambient temperature accompanied by solar irradiation on the PV system's panels through the representation of the relationship between solar irradiation, generated power, and ambient temperature.

Figure 4.16 shows the variation in the daily solar irradiation against the generated power for the studied period. It is seen from the pattern of the graph that solar irradiation and generated power are correlated with each other. The statistical analysis shows that the value of the correlation coefficient (R^2) ranges from 0.9719 to 0.9849, confirming a strong positive correlation between solar irradiation and generated power. On the other hand, the linear relationship between solar irradiation and electricity production is clearly apparent when a winter day is compared to a summer day.

Figure 4.17 presents the effect of elevated ambient temperatures on the generated power, showing the inverse relationship. It can be seen in the figures that the daily ambient temperature ranges from 30 °C to 50 °C. These increases caused reductions in generated power, especially during stressful periods. These findings confirm the results of other researchers who have investigated this point, affirming the observed reductions in power generation under these conditions [120].

Solar PV panels deployed in desert regions experience accelerated degradation compared to installations in other regions. This degradation is attributed to the harsh climate, as mentioned before. Solar irradiation plays a significant role in various degradation modes, manifested by encapsulant discoloration and delamination in PV modules. Moreover, it has been reported that EVA browning is frequently reported in this region, leading to significant losses in short-circuit current [23], [24], [96], [97], [100], [121]. Additionally, high ambient temperatures can greatly accelerate the degradation process and therefore pose thermo-mechanical fatigue, leading to increased series resistance, cell cracks/corrosion, delamination, and frame breakages, also the large variations in module and ambient temperatures can cause many defects [93], [109]. These degradations negatively affect the overall performance of the PV system.

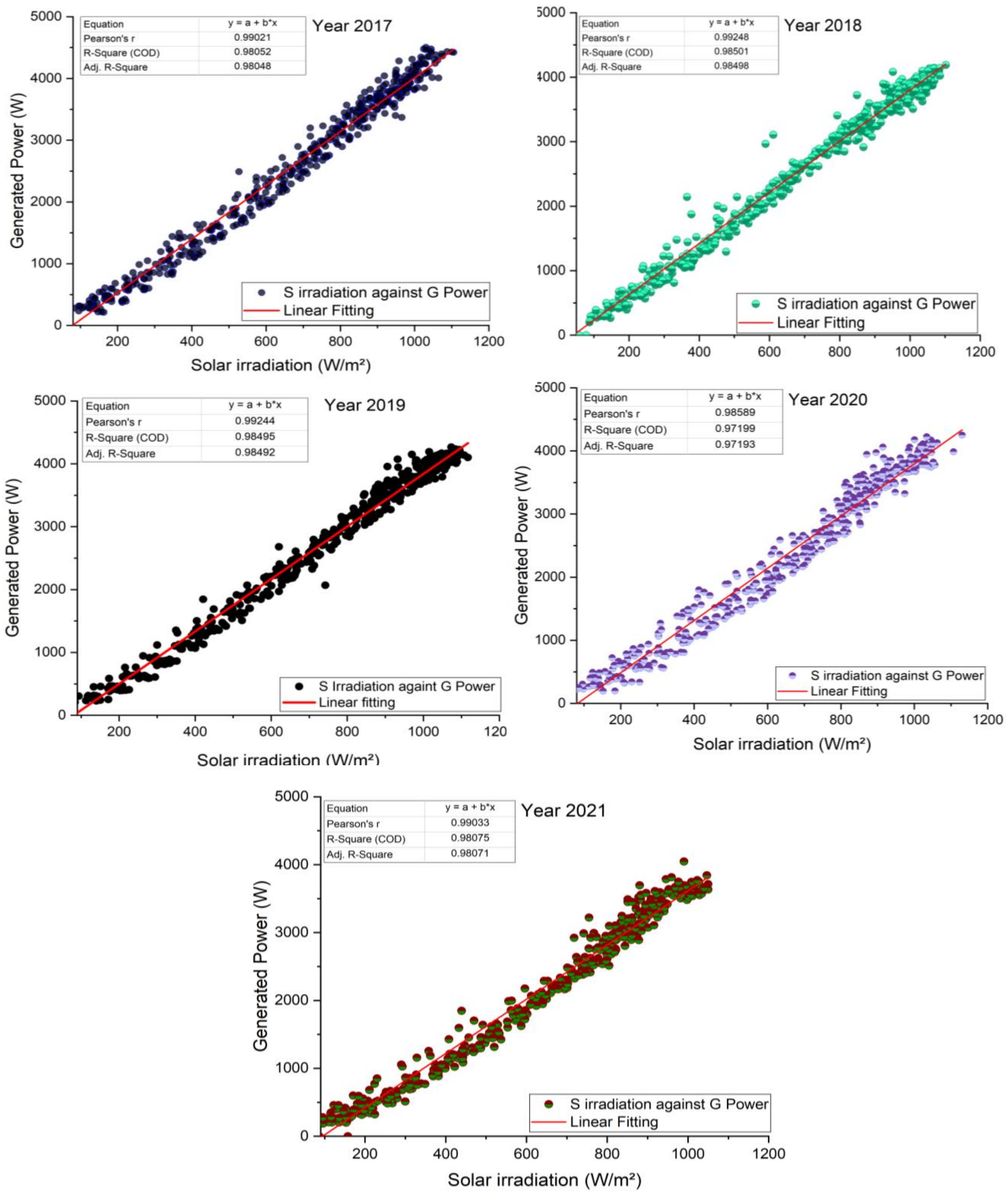


Fig 4.16 Linear fitting of solar irradiation against generated power

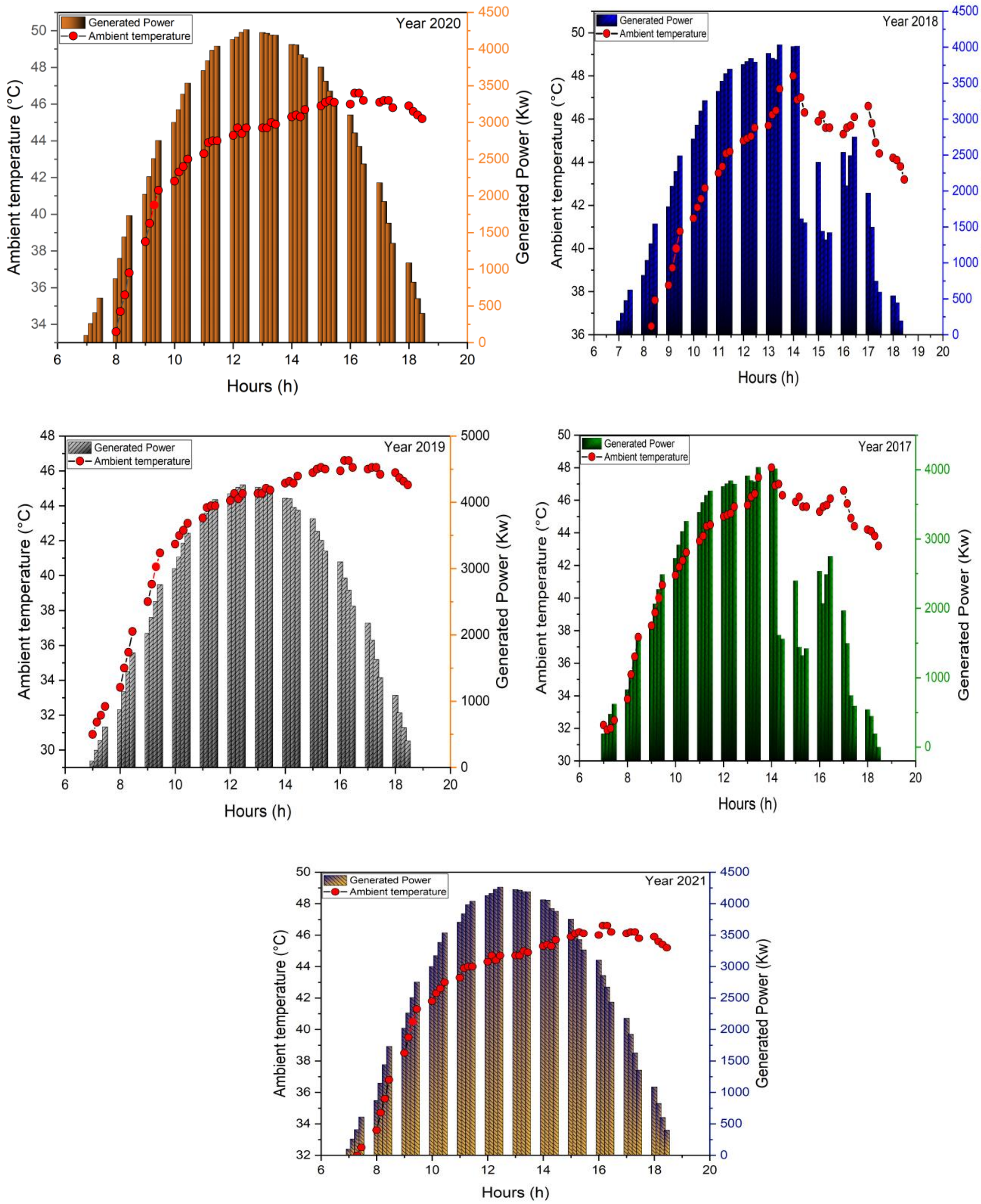


Fig 4.17 Effect of ambient temperature on the generated power

In this study, the assessment of grid-tied photovoltaic (PV) systems was focused particularly on DC side of power generation and based on the IEC 61724 Standard, involving the performance of energy yield (PV array YA, reference YR, and final YF), where these parameters characterize the performance of PV panels in terms of energy generation, that were briefly detailed in Chapter 2. In addition to that, to conduct a deep performance analysis, the study focuses on the summer seasons during the monitoring period, where the main stressful conditions (Solar irradiation and ambient temperature) reach their highest values.

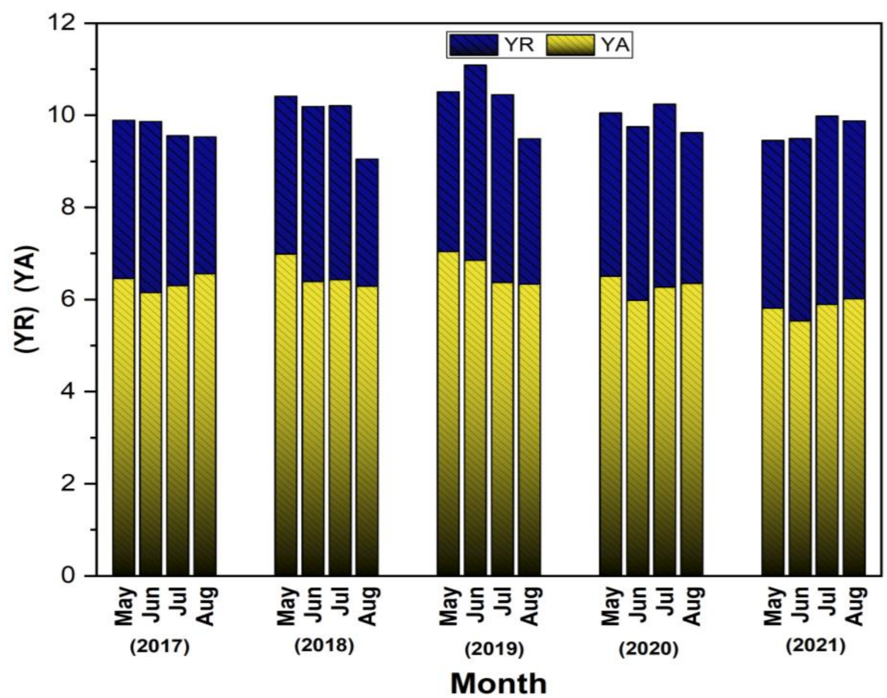


Fig 4.18 Energy yield performance for the monitored period during summer seasons

From figures 4.18 and 4.19, it appears that the combined effect of high ambient temperatures and high irradiation on the performance of PV systems. Where the performance ratio has shown a decrease that could reach 60% of its production capacity, based on these results, it can be concluded that they agree with the studies in the literature and previous studies in the same regions.

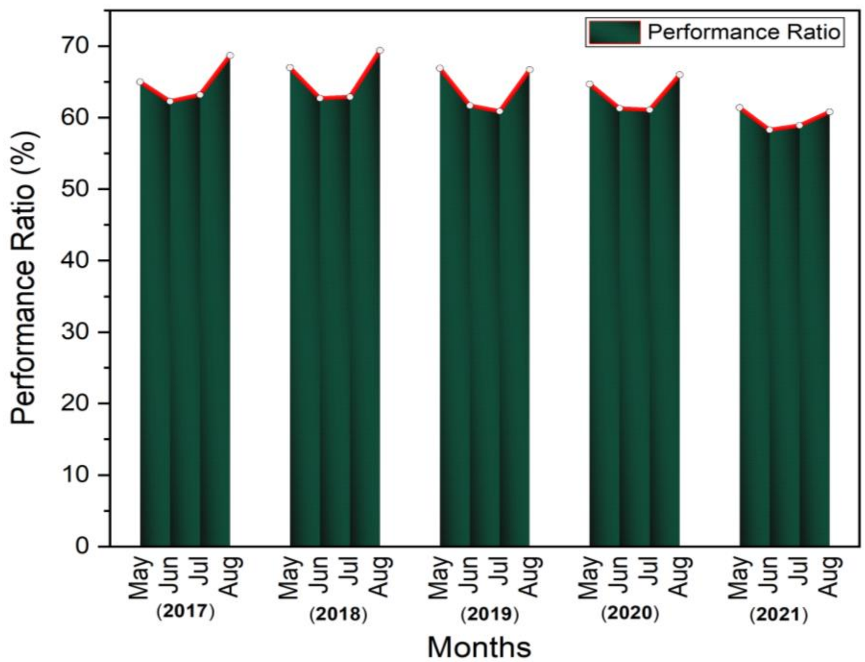


Fig 4.19 Performance Ratio for the monitored period during summer seasons

4.6 Conclusion

In harsh climates like deserts, every sub-component of PV system suffers from extreme operational conditions that affect their performance.

The performance monitoring of a photovoltaic power plant (6 MW grid-connected) that operates in a harsh climate revealed that its performance is heavily dependent on environmental conditions, especially ambient temperature and solar irradiation. Besides these two factors that have a contradictory effect on power generation, solar cell technology also contributes. Results showed that these combined factors reduced electrical capacity production by approximately 40%.

In conclusion, performance assessment of photovoltaic (PV) systems in harsh climates like deserts for a long time of monitoring is crucial for several reasons, such as maintenance, investment cost, and the long-term reliability of PV systems.

GENERAL CONCLUSION

GENERAL CONCLUSION

Desert regions offer high solar irradiation levels and two to three times more sunlight exposure compared to other site locations on an annual basis. As well as their suitable topography, which is characterized by vast, flat, and unoccupied areas that are generally far away from agricultural or urban uses, making desert regions desirable for solar photovoltaic deployment on large scales. These factors provide benefits to the economic, social, and environmental benefits of desert-based solar PV installations, providing a sufficient electricity supply, and supporting sustainable and clean energy solutions.

At the same time, the harsh environmental conditions that are uniquely present in combination in these areas, such as high ambient temperatures, intense solar irradiation, dusty environments, high UV doses, and other conditions that are typically found in arid climates, impact the installed PV modules under real operational conditions to a certain degree.

Under real operational conditions, photovoltaic (PV) modules are exposed to different external stress factors that can gradually affect their performance and operational lifetime. Typically, solar PV modules do not match the environmental requirements of desert locations, where these environmental factors influence photovoltaic panels, leading to degradation phenomena and failure modes over a short time for each module component.

To this matter, the experimental study in chapter 3 that was conducted at the unit of renewable energy in Saharan middle (URER-MS) in Algerian desert due to its harsh environmental conditions to relate the PV panels' performance and the most frequent failure modes that can appear on standard PV to the environmental conditions in this region, reaffirms that desert climates are environments that stress the modules far stronger than other environments, and therefore failure of PV panels appears within the first few years of the operation. The study also categorized failure modes and performance analysis of standard modules on the basis of data provided by the results of the characterization by using a Solmetric PV tracer and visual inspection. It found that the PV modules that have been exposed to stressor factors like high ambient temperature and solar irradiations suffer high discoloration degrees manifest in browning and dark browning discoloration and other defects like thermo-fatigue defects, accompanied by significant degradation in electrical performance highlighted by a decrease in Voc, Isc, and FF resulting in a big drop in output power, reaching a degradation rate of up to 3%/year, which is more than the expected degradation rate defined by the manufacturer by 1%/year.

GENERAL CONCLUSION

The experiments carried out in Chapter 4 aim to provide more information regarding the performance of photovoltaic power plant (6 MW grid-connected) that operates in the harsh climate of the Algerian desert at Zaouiet Kounta for over a five-consecutive-year monitoring period. Based on the experimental results obtained during the monitoring period the performance analysis revealed that the PV stations' performance is heavily dependent on ambient temperature and solar irradiation, where the combined factors reduced electrical capacity production by approximately 40%.

The thesis will provide knowledge and be beneficial in further studies on the degradation of PV modules in desert regions. In addition, the thesis contains rich information for an overview of environmental stressor factors in the desert region that can be helpful for researchers and laboratory tests for similar conditions to improve the design, choice of materials, operational lifetime, and cost-effectiveness of solar PV modules in terms of durability and reliability to be adequate for deployments on a large scale for such conditions, as well as, reducing electricity generation costs by photovoltaic power sources in desert regions to move toward renewable and clean energies.

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