République Algérienne Démocratique et Populaire
Ministère de l'Enseignement Supérieur et de la Recherche Scientifique
Université Kasdi Merbah Ouargla

Faculté Des Hydrocarbures, Des Energies Renouvelables, Des Sciences De La Terre Et De L'univers
Département Des Energies Renouvelables

Thèse

Présenté pour l'obtention du diplôme de

Doctorat 3ème cycle

Spécialité : Génie Mécanique
Option : Energies renouvelables

Présenté par :

DIDA Mustapha

Intitulé de la thèse :

Etude et amélioration des systèmes de conversion photovoltaïque dans les zones arides et semi-arides

Soutenu publiquement le : 16/12/2021

Devant le jury composé de :

Ahmed	DJAFOUR	Pr.	Président	Université Kasdi Merbah Ouargla
Slimane	BOUGHALI	Pr.	Encadreur	Université Kasdi Merbah Ouargla
Djamel	BECHKI	Pr.	Co- Encadreur	Université Kasdi Merbah Ouargla
Abdelkrim	KHELIFA	MCA	Examinateur	URAER Ghardaia
Abdelmalek	ATIA	MCA	Examinateur	Université du El-Oued
Yacine	MARIF	MCA	Examinateur	Université Kasdi Merbah Ouargla

Année universitaire: 2021/2022

People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
Kasdi Merbah University Ouargla
Faculty of Hydrocarbons, Renewable Energies and Earth and Universe Sciences
Renewable Energies Department

Thesis Presented in Partial Fulfilment of the Requirements of Doctorate degree in Mechanical Engineering

Option: Renewable Energies

Presented by:

DIDA Mustapha

Entitled:

Study and amelioration of photovoltaic conversion systems in arid and semi-arid areas

Discussed publicly on: 16/12/2021

Before the jury composed of:

Ahmed	DJAFOUR	Pr.	Chairman	Kasdi Merbah University Ouargla
Slimane	BOUGHALI	Pr.	Supervisor	Kasdi Merbah University Ouargla
Djamel	BECHKI	Pr.	Co- Supervisor	Kasdi Merbah University Ouargla
Abdelkrim	KHELIFA	Dr.	Examiner	URAER Ghardaia
Abdelmalek	ATIA	Dr.	Examiner	El-Oued University
Yacine	MARIF	Dr.	Examiner	Kasdi Merbah University Ouargla

Academic year: 2021/2022

To begin with, I thank Allah the Almighty, for giving me the courage and the will to do this research work.

My warm thanks imperatively go to my parents for their love, care, constant encouragement and prayers all the time.

I would like to express my profound and deep gratitude to my supervisor Prof. Slimane BOUGHALI and my co-supervisor Prof. Djamel BECHKI, whom I respect deeply, for their unconditional trust, enduring patience and unremitting help throughout the entire process.

Many thanks to Prof Hamza BOUGUETTAIA for his invaluable guidance and immense help to elaborate and improve this work.

I would like to express my sincere gratitude to the committee members prof. Ahmed DJAFOUR and Dr. MARIF Yacine from Ouargla University, Dr. Abdelkrim KHELIFA from URAER Ghardaia, and Dr. Abdelmalek ATIA from El-Oued University who accepted to read, evaluate and examine this thesis.

I am also grateful to all of the researchers and PhD students of the LENREZA laboratory in the University of Kasdi Merbah, Ouargla for their support, insightful suggestions and precious comments in conducting my research.

I am indebted to my dear friends and everyone who contributed and helped in conducting this work. Thanks to all that who were always here for me wherever and whenever I needed them.

Finally, I hope this modest work will rise to meet the level of the anticipated expectations.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Nomenclatures

G	Solar radiation ($W.m^{-2}$)
T	Temperature (C°)
t	Time (s)
V	PV modules' voltage (V)
I	PV modules' current (A)
P_m	Maximum output power (W)
I_{sc}	Short-circuit current
V_{oc}	Open-circuit Voltage
T_a	Ambient temperature (C°)
T_c	Temperature of cooled PV module (C°)
T_r	Temperature of reference PV module (C°)
FF	Fill Factor
I_m	Maximum current
V_m	Maximum voltage
W	Watt

Abbreviations

PV	Photovoltaic
STC	Standard Test Conditions
SKTM	Shariket Kahraba wa Taket Moutadjadida
XRF	X-Ray Fluorescence
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
RES	Renewable Energy Sources
CSP	Concentrating Solar Power
REEEDP	Renewable Energy and Energy Efficiency Development Program
LPG	Liquefied Petroleum Gas
OPEC	Organization of Petroleum Exporting Countries
Mtoe	Million tonnes of oil equivalent
Mt	Million tonnes

G*reek symbols*

δ	Thickness (mm)
ρ	Density (kg/m^3)
η	Efficiency

GENERAL INTRODUCTION

The global electricity consumption has been increasing continuously at the rate of 3% per year; mainly due to the increase of population, techno economic development and the people's needs to create a comfortable life environment (Rawat et al., 2016). However, the overuse of conventional fossil fuels to cover the entire energy demand has negative impacts on the environment and leads to an increase in global warming, air pollution, climate change and acid rain. In addition, these traditional resources are predicted to be exhausted within the next few centuries (Sampaio and González, 2017). Recently, in order to eliminate the above problems and to deal with the environmental and economic challenges that are involved in electricity generation, renewable and sustainable energy sources have supposed to be considered as promising power generating sources as they are secure, clean and environment friendly (Ibrahim et al., 2017). Among several sources of renewable energy, solar energy is an unexhausted and clean energy source which supplies the Earth by 4000 trillion kWh of insolation daily (Boughali et al., 2009; Joshi and Arora, 2017). Different technologies such as photovoltaic, photothermal and photochemistry are used to convert solar radiation into electric, thermal and chemical energy respectively (Rawat et al., 2017).

Electricity can be generated from solar energy in two main ways, photovoltaic systems (PV) and concentrating solar power systems (CSP). However, PV technology is the most used application of sunlight for electricity production in household autonomous systems or in grid connected systems. The solar PV technology has been deeply investigated and developed within the last two decades and has become one of the most important sources of renewable energy after hydro and wind power (Ju et al., 2017). PV power generation is characterised by small footprint, low maintenance cost and other many advantages such as operational simplicity, absence of moving parts and noiseless operation (Ikkurti and Saha, 2015). Moreover, the significant decrease in PV modules cost, that contributes importantly to the total PV system cost, led to a substantial expansion in the installation of PV systems and large mega scale PV power plants all over the world (Xue, 2017). By the end of 2018, the worldwide solar PV power generation has increased by 31% and represented the highest absolute generation growth (+136 TWh) of all renewable energy technologies. Moreover, the PV power generation has been expected to increase from 580 TWh in 2018 to around 3300 TWh in 2030 (IEA). The photovoltaic power conversion is the direct conversion of sunlight into electricity by the use of semiconductor materials, which are the main compound of PV cells manufacturing.

Semiconductor materials are classified into different groups, specifically silicon PV cells such as monocrystalline (m-Si) and polycrystalline (p-Si), thin film PV cells such as copper indium gallium selenide (CIGS), Gallium arsenide (GaAs), cadmium telluride (CdTe) and there are also dye-sensitized solar cells and organic/polymer material cells. However, monocrystalline (m-Si) and polycrystalline (p-Si) silicon cells are the most widely used solar cells in PV systems due to their reasonable conversion efficiency, investment cost and reliable service lifetime (Islam et al., 2016).

Presently, solar PV cell conversion efficiencies for commercially available PV modules are around 14-25% with a service lifetime up to 20-25 years. However, the efficiency of these systems is lower when operating in real outdoor operating conditions than under controlled laboratories. This is mainly due to the sensitivity of the cells to environmental factors such as ambient temperature, relative humidity, irradiance intensity, dust deposition, wind velocity and ultraviolet irradiation (UV). Climatic parameters influence strongly on most of PV technologies and lead to a significant diminishment in their performance and service lifetime (Rajput and Yang, 2018).

Most of the photovoltaic power plants are installed in arid and desert environments where the highest solar irradiation values and the abundance of unused lands. However, these lands are usually dusty or sandy. This increases the soiling issue of PV modules; dust deposition on the surface of the module decreases glass cover transmittance, which has an important influence on the PV conversion efficiency due to the reduction of received solar irradiation and the possibility of partial shading formation because of the non-uniform distribution of sunlight (Mussard and Amara, 2018). Moreover, these zones also characterised by the high ambient temperatures, which limits the efficiency of PV conversion as the efficiency of PV panels drops by 0.5% with every 1 °C increase in operating temperature (Abd-Elhady et al., 2018; Ogbomo et al., 2018).

Algeria is characterised as one of the regions with the highest mean annual solar radiation values worldwide (Bechki et al., 2010; Nadir et al., 2019). However, Algeria comprises mostly of arid and semi-arid regions, and it is one of the most countries suffering from PV performance degradation due to the accumulation of dust and high ambient temperatures. Although, the number of research studies concerning this issue is very rare (Gharzi et al., 2020; Maghami et al., 2016; Mani and Pillai, 2010).

In this regard, the present thesis is particularly interested in studying and contributing to mitigate the effect of environmental factors on the efficiency of photovoltaic systems installed in hot arid and semi-arid locations. A number of experiments under real outdoor conditions of a Saharan region (Ouargla, South of Algeria) were conducted to investigate the effect of climatic factors (especially dust deposition and ambient temperature) that have the greatest impact on the PV modules performance degradation in arid areas.

This thesis is organised as follows:

After a general introduction, the first chapter presents introductory knowledge on global and local electricity power statistics and briefly examines each of the potential and share of renewable energy sources. The national program of renewable energy was discussed too. Moreover, this chapter introduces the evolution of photovoltaic energy exploitation, different technologies, characteristics and applications.

The second chapter provides a state of art and literature review on the influence of various environmental factors on the efficiency of photovoltaic modules. The impact of solar irradiation, shading, dust deposition and operating temperature on PV performance was evaluated based on different previous conducted research studies around the world. Mitigation solutions and techniques of these factors influence were discussed. Based on the literature review analysis, we were able to get a key idea about the work we will be doing in the next chapters.

The third chapter devoted mainly on the experimental performance parameters evaluation of the impact of dust deposition on the performance of PV systems. Experiments were carried out at the laboratory of new and renewable energy in arid and Saharan zones (LENREZA), Ouargla university, and in the SKTM (30 MW) PV power plant under Saharan weather conditions of the Algerian South (Ouargla city).

In the fourth chapter, we present an experimental evaluation of a developed cooling system to reduce the effect of high operating temperatures on PV modules and improve their efficiency. A passive cooling system based on water evaporation and capillary action of burlap was designed, developed and fabricated, the obtained results and its feasibility were discussed.

Finally, a general conclusion that gathers all the results that can contribute to improving the PV conversion efficiency in arid and semi-arid regions.

1. INTRODUCTION

Solar photovoltaic (PV) energy is the most promising of renewable energies, it has many advantages such as being abundant, clean, non-polluting and reliable. It also contributes to reduce CO2 emissions and protect the environment. This chapter gives a brief overview on solar photovoltaic energy with a presentation of its potential, installed capacities, conversion principle, main technologies classification and different PV systems applications. Moreover, the Algerian program of renewable energies has also been discussed in this chapter.

2. GLOBAL ELECTRICITY CONSUMPTION

The global electricity production rose by 3.9% in 2018 to reach about 26730 TWh. Combustible fuels share estimated by 66.3% of the total world electricity production (of which: 63.9% of fossil fuels and the rest 2.4% of biofuels and waste). Republic of China and the United States were the largest consumer countries of electricity by 26.9% and 17.5%, respectively, and they represent together over 40% of the global consumption (IEA, 2020).

2.1. Global renewable energy potential

Actually, coal, oil and natural gas are the main sources of electrical energy with a contribution of about (65%). However, those sources are harmful to the environment due to the greenhouse gases resulted from their combustions, in addition to the fact of their exhaustion with time is imperative. Renewable energy sources (RES) can be a good exchange of fossil fuels to cover the energy needs. Supplied mainly by solar, wind, geothermal and hydropower. This energy sources utilisation is clean and friendly to the environment without greenhouse gases emission, which made them the future energies.

According to the annual report "Renewable capacity statistics 2020" of the International Renewable Energy Agency (IRENA, 2020), a summary of the evolution of the cumulative capacities of electricity production from the main renewable sources in the world during the ten recent years (2010-2019) is displayed in **Figure 1-1.**

A brief analysis of the presented statistics already makes it possible to identify the first elements that could help to orient objectively the choices of renewable sources to be developed as a part of the energy transition. To date, the global installed capacity of renewable energy for electricity generation is estimated by 27.3% **Figure 1-2** (REN21). According to the installed capacities, it seems that the hydroelectricity contribution remains dominant by more than 47% in terms of the renewable electricity generation in the world. However, it should be noted that this share, which was more than 75% only ten years ago (2010), has steadily declined to give way, mainly to wind (23.5%) and solar photovoltaic (22.8%) electricity in 2019 compared to a contribution of (14.8%) and (3.3%) respectively, in 2010. In the other hand, the contribution of biomass and geothermal energy technologies to the renewable electricity production remains low (5.5% in 2019) with a very limited development (IRENA, 2020).

More than 200 GW of new renewable energy production capacity was installed in 2019, increasing the global total of 2588 GW by the end of the year. The implementations were better than 2018 levels, maintaining an average growth rate by more than 8% of installed renewable energy capacity in the last five years (REN21). This high increase of the renewable electricity production based on different technologies, especially wind and solar photovoltaic energy, clearly reflects the real desire of the world to achieve an energy transition and disposal of the fossil energy resources dependence.

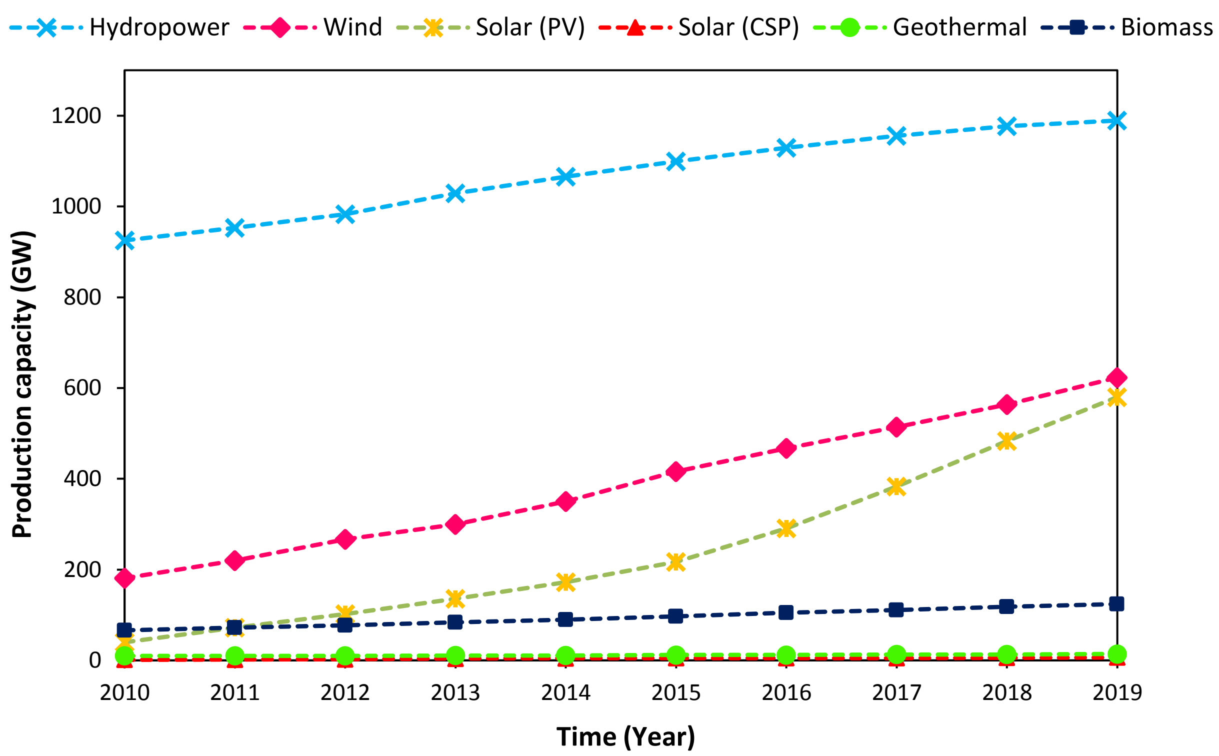


Figure 1-1 Evolution of renewable electricity production capacity (2010-2019).

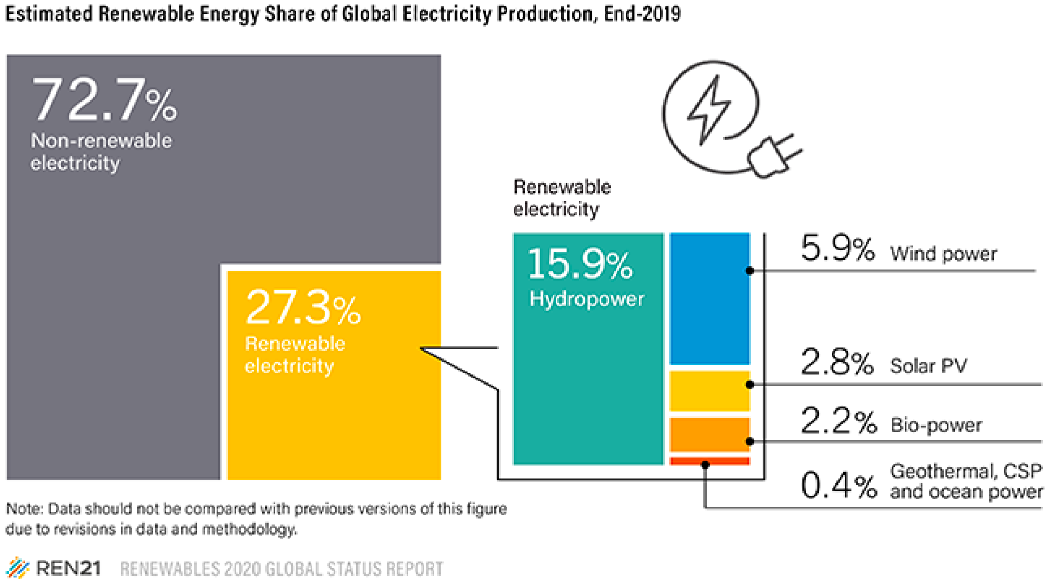


Figure 1-2 Estimated renewable energy share of global electricity production (REN21).

2.2. Global photovoltaic potential

Sun is the most powerful and free source of energy which supplies the Earth by 4000 trillion kWh of insolation daily (Joshi and Arora, 2017). Photovoltaics is a form of solar energy that produces electrical energy by the direct transforming of solar radiation. It has various advantages that arguably make this energy technology as the best renewable solution for the future of the world's energy demand. The advantages consist in the high abundance of solar energy in vast areas over the world, its inexhaustibility nature, ecosystems friendly, easy application (villages and homes). According to the (IRENA, 2020)**,** electricity production capacity from solar photovoltaic energy showed the most evolution rate from 40.3 GW in 2010 to 580.2 GW in 2019 which represent roughly a quarter of renewables.

As it can be seen from **Figure 1-3** China republic, Japan and Germany are the most PV electricity producer's countries over the world. However, the photovoltaic contribution is only about of 2.8% of the global electricity generation, which is still very low compared to the global solar potential. The solar energy that reaches the Earth's terrestrial surface in only 1 h is enough to cover a one-year entire global energy consumption (Abd-Elhady et al., 2018).

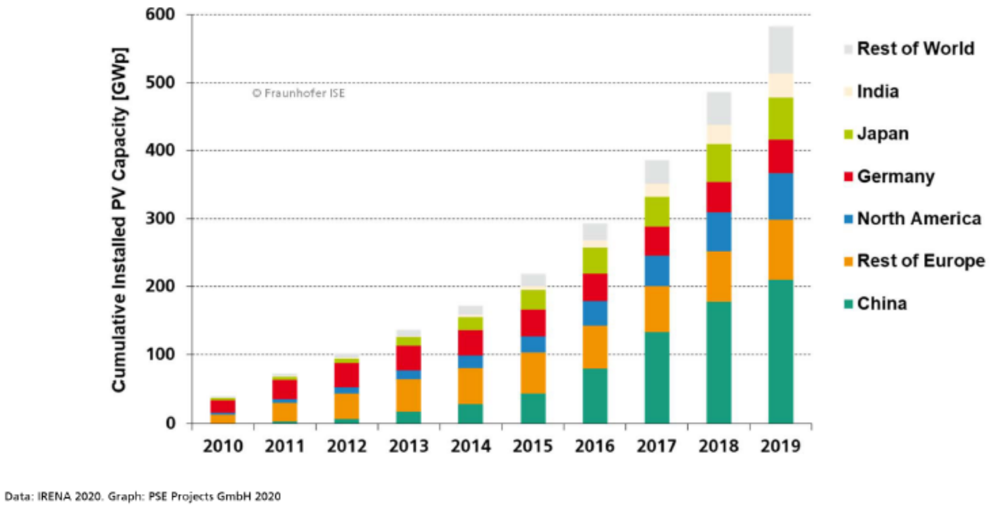


Figure 1-3 Evolution of solar photovoltaic electricity production capacities and distribution around the world (2010-2019) (IRENA, 2020).

2.3. Photovoltaic market

Over the past decade, PV power generation costs have declined sharply, driven by technologies improvements, competitive supply chains and developer experience growth. Costs for electricity generation from solar photovoltaics (PV) dropped by 82% in the last ten years (2010-2019) reaching (USD 0.068 / kWh) in 2019 compared to (USD 0.378 / kWh) in 2010 (IRENA, 2020)**.** In addition, PV electricity generation price showed the highest falling rate between 2010 and 2019 compared to other renewable sources (CSP 47% and onshore Wind 39%) **Figure 1-4**, which made it incrementally the cheapest source of new electricity, offering an immense potential to stimulate the global economy and create new job chances for people.

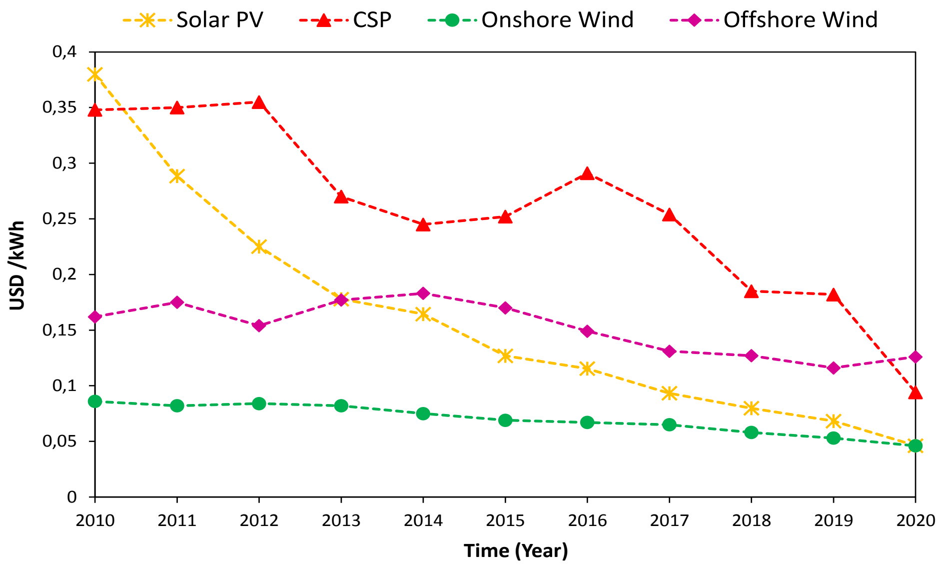


Figure 1-4 Evolution of electricity production costs for different technologies (IRENA,2020).

3. ENERGY PROFILE IN ALGERIA

Algeria is characterised by diversified and significant natural resources, gas reserves in Algeria being among the highest in the world, as immense fields of oil and other resources such as (Gold, Iron, Zinc, Phosphate, Uranium, etc...) (Rahmouni, 2018). Moreover, Algeria plays a vital role in the world energy markets, both as an important producer and exporter of hydrocarbons, as well as a promising participant in the market of renewable energy due to its featured geographical location and miscellaneous natural resources.

3.1. Energy production

The primary energy commercial production recorded a stabilisation in all product types until 2016 where a notable augmentation in the production of natural gas has recorded reaching 92106 Ktoe in 2018 as presented in **Figure 1-5**. Which partially compensated the decrease in the liquids production (petroleum and LPG) due to the implementation of the convention for the reduction of OPEC production.

3.2. Energy consumption

Fossil fuels represent the most important part of energy consumption in Algeria. Final consumption rose reached to 48.1 Mtoe in 2018, which is reflecting a significant increase of (+ 7.8%) compared to 2017, pulled mainly by that of natural gas followed by petroleum products and LPG.

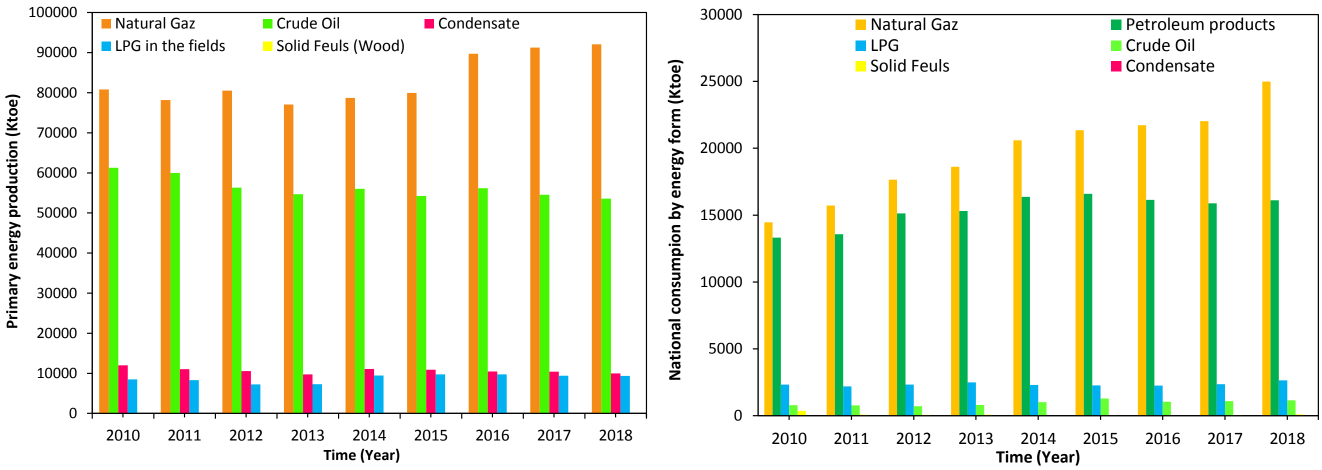


Figure 1-5 Energy production and consumption in Algeria (MEM).

3.3. Electricity consumption

The electricity sector has undergone a major development in response to a desire to generalise household electrification throughout the national territory. This generalisation will have a major implication on the development of distribution and transmission networks. The Sonelgaz Company held a monopoly on the production, transmission and distribution of electricity as well as the transmission and distribution of gas. Today, Sonelgaz occupies a privileged position in the country's economy as responsible for supplying more than six million households with electricity and a geographical coverage of nearly 99% in electrification (Gouareh, 2017).

In recent years, electricity consumption in Algeria has increased significantly due to high population density and an increase in people’s needs. The electricity consumption in Algeria increased enormously from 36.58 Twh in 2010 to 66.67 Twh in 2018, which is representing an augmentation of (+10%/year) **Figure 1-6** (IEA, 2020). The peak of electricity consumption values for the electricity system in Algeria, are recorded mainly during the daytime and in the summer season months. Which needs to head and to pay more attention to renewable energy sources, especially solar energy technologies that can contribute strongly in the meeting of demand peak values (Haddad et al., 2017).

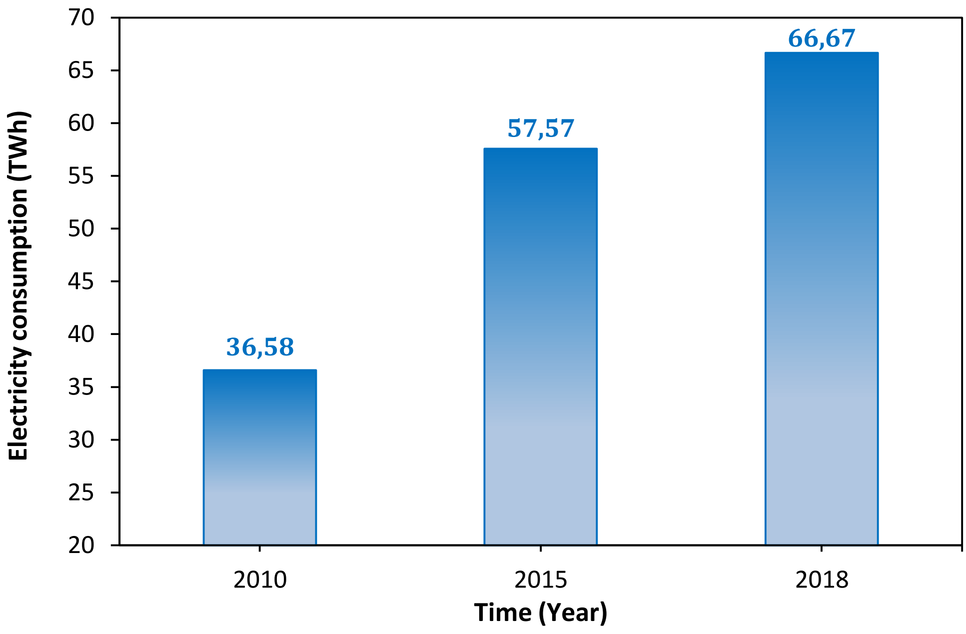


Figure 1-6 Evolution of electricity consumption in Algeria (2010-2018) (IEA, 2020).

3.4. CO2 emissions

Due to the using of fossil fuels as the main energy source for electricity production, transport and other energy industries, Algeria is considered as one of the most CO2 emitters among world countries. According to the International Energy Agency statistics (IEA, 2020) the CO2 emissions in Algeria has increased from 95.5 Mt in 2010 to 137.3 Mt in 2018 **Figure 1-7.** Therefore, Algeria should take more efforts towards the integration of renewable energies to reduce CO2 emissions one hand and to keep a clean and healthy environment on the other hand.

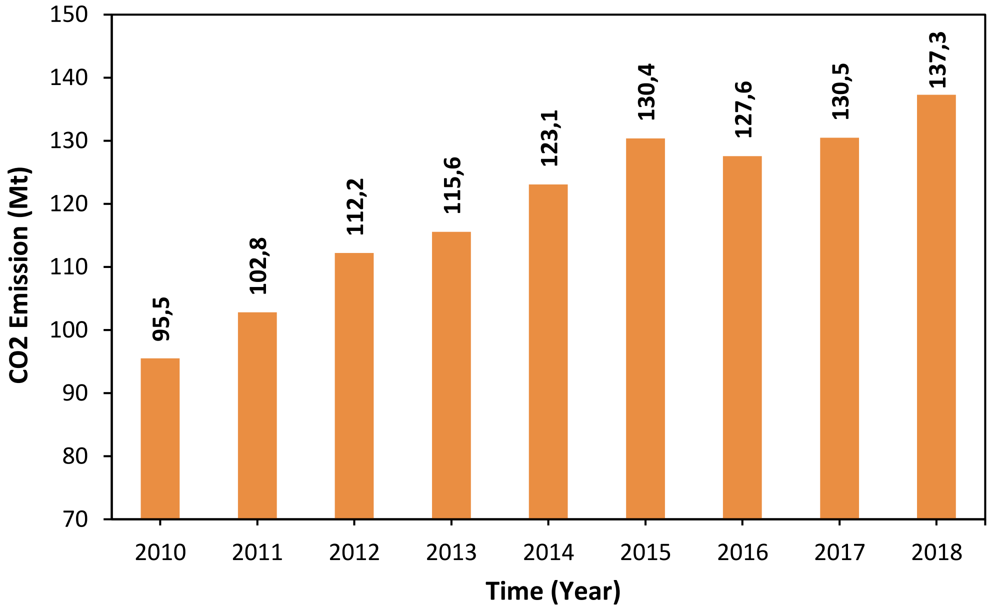


Figure 1-7 Evolution of CO2 emission in Algeria (2010-2018) (IEA, 2020).

3.5. Participation of renewable energy

Renewable energies are a promising alternative to fossil fuels to meet the current and future energy requirements, and help to support sustainable economic growth and fight climate change. Algeria is a very huge country with a very diverse climate, it has an important potential of renewable energy, which are mainly Solar, Wind, Geothermal, Water and even Biomass. However, the present contribution of renewable energies is very low in the total energy balance compared to the RES capacities, but the Algerian government in 2011 founded an ambitious development program for the exploitation and utilisation of RES in electricity generation.

3.5.1. Renewable Energy and Energy Efficiency Development Program (REEEDP):

Since 2011, the Algerian government has focused on new sources of renewable energy by launching a renewable energy and energy efficiency program. The national program of Renewable Energy and Energy Efficiency Development (REEEDP) has an overall objective to produce a power of renewable origin (Solar and Wind) of a 22,000 MW By 2030, of which 12,000 MW will be dedicated to covering the national electricity demand and 10,000 MW for exportation (CEREFE, 2020).

The first version of (REEEDP) has been updated in 2015, which is mainly motivated by notable changes in the world in terms of investment costs and the production of electricity from RES. In addition, the energy efficiency program was created essentially to decrease the energy consumption augmentation with engagement on various economic sectors including transportation, industry and buildings, and to reduce the CO_2 emissions. **Table 1-1** and **Figure 1-8** show the REEEDP implementation plan revised in 2015.

Table 1-1 The REEEDP implementation plan revised in 2015 (CEREFE, 2020).

	1st Phase 2015-2020 (MW)	**2nd Phase 2021-2030 (MW)**	**Total (MW)**
Photovoltaic	3000	10575	13575
Wind	1010	4000	5010
CSP	-	2000	2000
Cogeneration	150	250	400
Biomass	360	640	1000
Geothermal	05	10	15
Total	4525	17475	22000

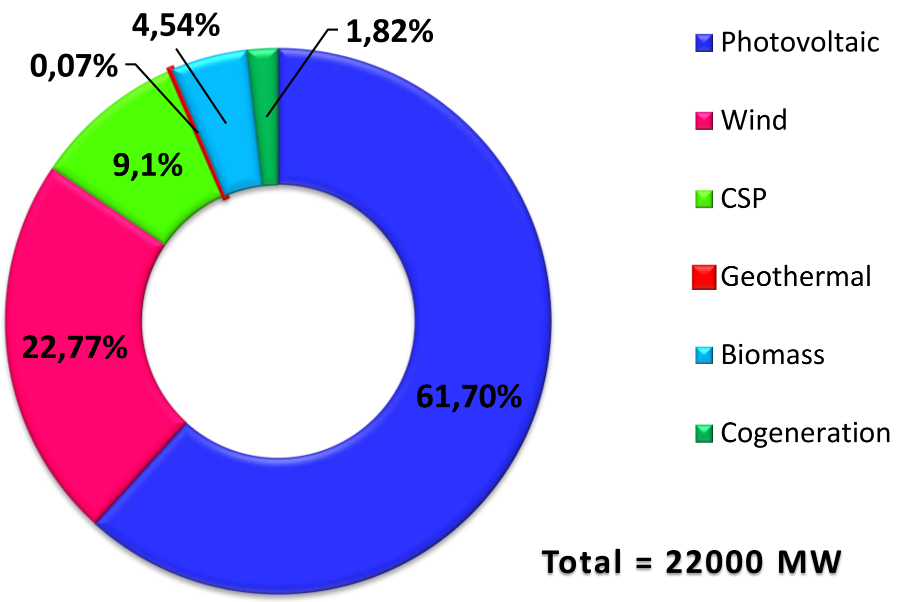


Figure 1-8 Objective of the Algerian renewable energy program by 2030 (CEREFE, 2020).

3.5.2. Photovoltaic potential in Algeria:

Algeria is characterised as one of the regions with the highest mean annual solar radiation values worldwide. The time of insolation through the almost of the Algerian territory exceeds 2000 h annually and could reach 3900 h (highlands and Sahara). On a (1 m^2) horizontal surface, The daily received energy is about 5 kWh through the major part of the country, or approximately 1700 kWh/m^2/year for the Northern and 2263 kWh/m^2/year for the Southern part (Yaiche et al., 2014).

Algeria is also characterised by abundant sunshine throughout the year, especially the Southern region (Sahara), low humidity and precipitation, and huge areas of unused flat ground neighbour of road networks and electricity transmission grids. Consequently, Algeria has an enormous potential for solar power generation compared to local, regional and global energy demands. Only about 10% of the Algerian Sahara surface could meet the EU energy demand (Stambouli et al., 2012). **Figure 1-9** shows the global horizontal irradiation and the photovoltaic power potential maps of Algeria. **Table 1-2** represents in details the solar energy potential in Algeria.

Table 1-2 Solar potential in Algeria (Stambouli et al., 2012).

Areas	**Coastal area**	**High plains**	**Sahara**	**Total**
Surface (%)	4	10	86	100
Area (Km^2)	95,270	238,174	2,048,297	2,381,741
Mean daily sunshine duration (h)	7.26	8.22	9.59	
Average duration of sunshine (h/year)	2650	3000	3500	
Received average energy ($kWh/m^2/year$)	1700	1900	2650	
Solar daily energy density (kWh/m^2)	4.66	5.21	7.26	
Potential daily energy (TWh)	443.96	1240.89	14,870.63	16,555.48

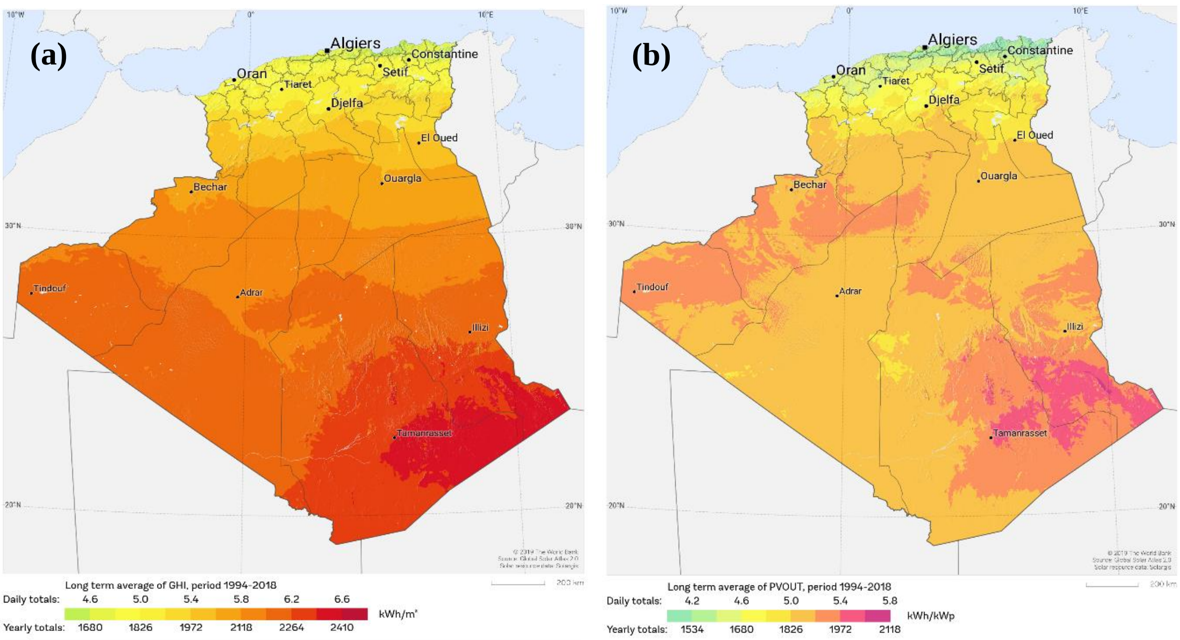


Figure 1-9 (a) Global horizontal irradiation, (b) Photovoltaic power potential of Algeria (Solargis).

3.5.3. Installed PV systems in Algeria

Algeria's energy strategy is based mainly on accelerating of solar energy development. Several solar photovoltaic projects in different regions of the country have been launched by the government with a total capacity of around 3000 MW and are scheduled to be accomplished by 2020 (MEM). However, it is well observed that to date (2020) the planned (REEEDP) schedule has not been performed. Actually, the only apparent activity on the ground in the field of renewable energies in the country since 2015, has essentially been dominated by the reception of photovoltaic solar plants with a total capacity of 343 MW of the program launched in 2014 by SKTM (MEM). **Figure 1-10** displays the installed PV projects localisation of (REEEDP), and **Table 1-1** shows the details of each site, startup date and installed capacity. **Figure 1-11** presents a comparison between the planned photovoltaic electricity production of (REEEDP) and the embodied efforts on the ground by 2020.

Moreover, SONATRACH has put in service in 2018 a first 10 MW photovoltaic solar power plant in Bir-Rebaa North (BRN), wilaya of Ouargla, as a part of its SH 2030 strategy which aims to deploy a total capacity of 2300 MW in solar energy by 2030. Therefore, to date only a total capacity of 354.1 MW has been accomplished (22 solar PV power plants of 343 MW, a pilot PV power plant of 1.1 MW are built by SKTM / SONELGAZ, and a 10 MW PV power plant built by SONATRACH) (CEREFE, 2020).

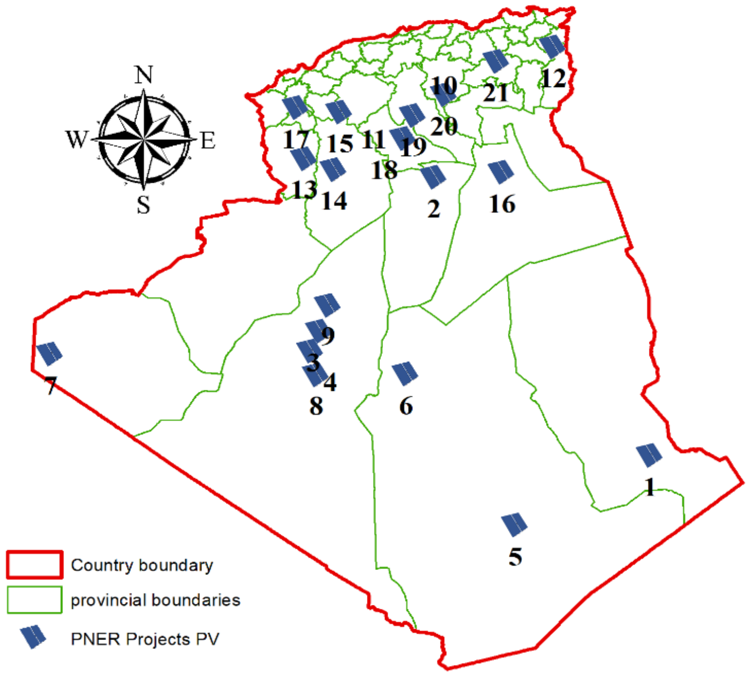


Figure 1-10 PV sites localisation of REEEDP (Settou et al., 2021).

Table 1-3 Description of installed PV project REEEDP (MEM).

N°	Wilaya	Power stations	Installed Capacity [M W]	Startup date
1	ILLIZI	Djanet	03	19/02/2015
2	GHARDAIA	Oued Nechou	1.1	10/07/2014
3	ADRAR	Kabertene	03	13/10/2015
4	ADRAR	Adrar	20	28/10/2015
5	TAMANRASSET	Tamanrasset	13	03/11/2015
6	TAMANRASSET	In-Salah	05	11/02/2016
7	TINDOUF	Tindouf	09	14/12/2015
8	ADRAR	Zaouiet-Kounta	06	11/01/2016
9	ADRAR	Timimoun	09	07/02/2016
10	DJELFA	Ain-El-Ibl (I)	20	08/04/2016
11	LAGHOUAT	El-Khnag (II)	40	26/04/2017
12	SOUK AHRAS	Oued-El-Keberit	15	24/04/2016
13	NAAMA	Sedrate-Leghzal	20	03/05/2016
14	EL BAYADH	Biodh-Sidi-Chikh	23	26/10/2016
15	SAIDA	Ain-Skhouna	30	05/05/2016
16	OUARGLA	El-Hadjira	30	16/02/2017
17	SIDI BEL ABBES	Telagh	12	29/09/2016
18	LAGHOUAT	El-Khnag (I)	20	08/04/2016
19	DJELFA	Ain-El-Ibl (II)	33	06/04/2017
20	M’SILA	Ain-El-Melh	20	26/01/2017
21	BATNA	Oued-El-Ma	02	16/01/2018
22	ADRAR	Reggane	05	28/01/2016
23	ADRAR	Aoulef	05	07/03/2016

As it can be seen from **Figure 1-10** and **Table 1-3** More than 75% of the installed PV projects in Algeria are installed in the middle and the Southern regions of the country such as (Laghouat, Djelfa, Adrar, Saida and Ouargla), which are characterised by the high solar intensity values and long sunshine time. However, in the same time these areas have a semi-arid and desert climate type that will influence certainly on the productivity and durability of PV systems due to the severe environmental conditions. The impact of different weather conditions that effect on the performance of photovoltaic systems will be discussed in details in the second chapter of the present thesis.

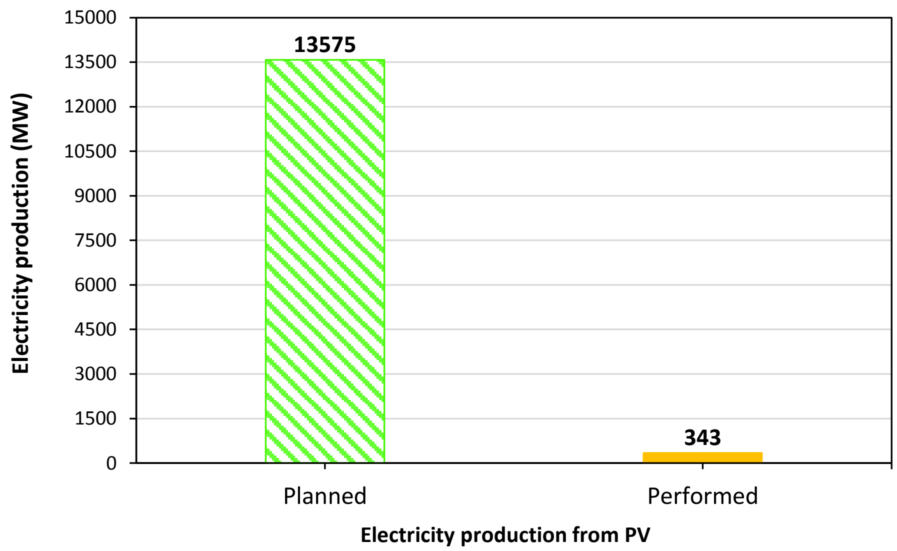


Figure 1-11 Plan of (REEEDP) for photovoltaic electricity production and the embodied efforts on the ground by 2020 (CEREFE, 2020).

4. PHOTOVOLTAIC CONVERSION

Photovoltaic conversion is the direct conversion of solar irradiation into electrical current based on the photovoltaic effect using solar cells. A PV cell is made from two semiconductor layers, one is P-doped (doped with boron) and the other is N-doped (doped with phosphorus) hence creating a PN junction with a potential barrier. The presence of the PN junction allows the existence of an electric field in the cell. As holes pass to the negative N-side and electrons pass to the positive P-side. This field leads to flowing negatively charged particles in one direction while positively charged particles in the other direction (Luque and Hegedus, 2011; Sampaio and González, 2017). Sunlight is composed of photons, which are simply small packs of electromagnetic radiation. When radiation of an adequate wavelength is received by cells, energy is transferred from the photon to an electron of the semiconducting material, leading it to jump to a higher energy situation called the band of conduction. In their excited situation in the conduction band, these electrons are free to pass through the semiconductor material, which creates an electric current in the PV cell (Selmi et al., 2014; Slaoui et al., 2017). **Figure 1-12** shows a schematic diagram of a PV cell.

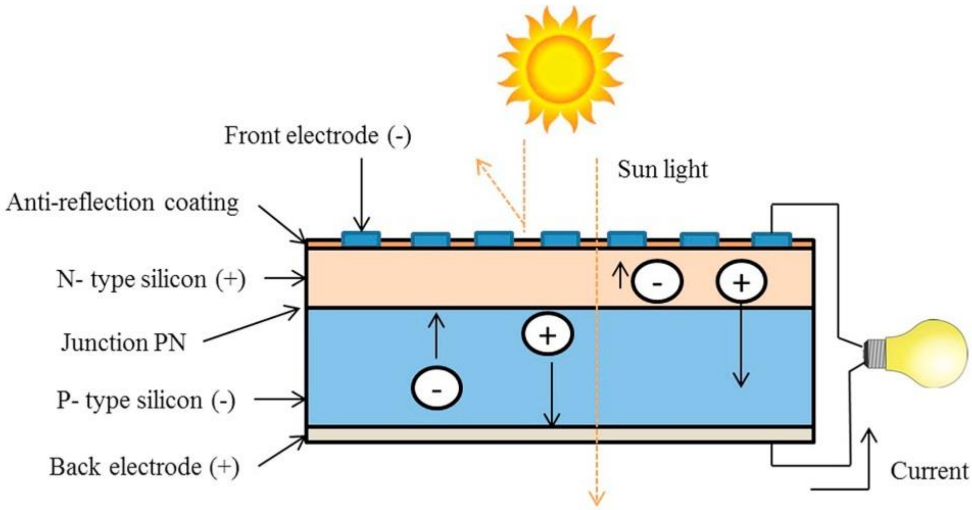


Figure 1-12 Schematic diagram of a PV cell (Sampaio and González, 2017).

4.1. Photovoltaic cells technologies

Photovoltaic solar cells manufactured with silicon are the most commercialised PV cells technology by share of 90% due to its high abundance, easy fabrication and reliability. However, other PV cells technologies are also used such as gallium arsenide (AsGa) which is characterised by a better electrical energy generation than silicon. But, this type of material is scarce in nature and so costly, it is usually used with spatial applications for its high efficiency. In addition, there are other materials with less use such as cadmium telluride (CdTe) diselenide, germanium (Ge), selenium (Se), and copper Indium (commonly called CIS), etc.… (Ogbomo et al., 2016). PV technologies can be classified to three main generations **Figure 1-13**. (El Chaar et al., 2011; Shukla et al., 2016), which are as follow:

- First generation photovoltaic cells, which are Silicon based PV cells including monocrystalline and polycrystalline Silicon.

- Second generation photovoltaic cells, including thin-film PV cells such as amorphous (a-Si), copper indium gallium diselenide (CIGS) and cadmium telluride/cadmium sulphide (CdTe/CdS), which aims to use less material whilst preserve the efficiencies of first PV cell generation.

- Third generation photovoltaic cells, including copper zinc tin sulfide (CZTS), a dye-sensitized solar cell (DSSC), organic, perovskite, polymer and quantum dot PV cells, which aims to reach high efficiencies but still use thin film second-generation deposition techniques.

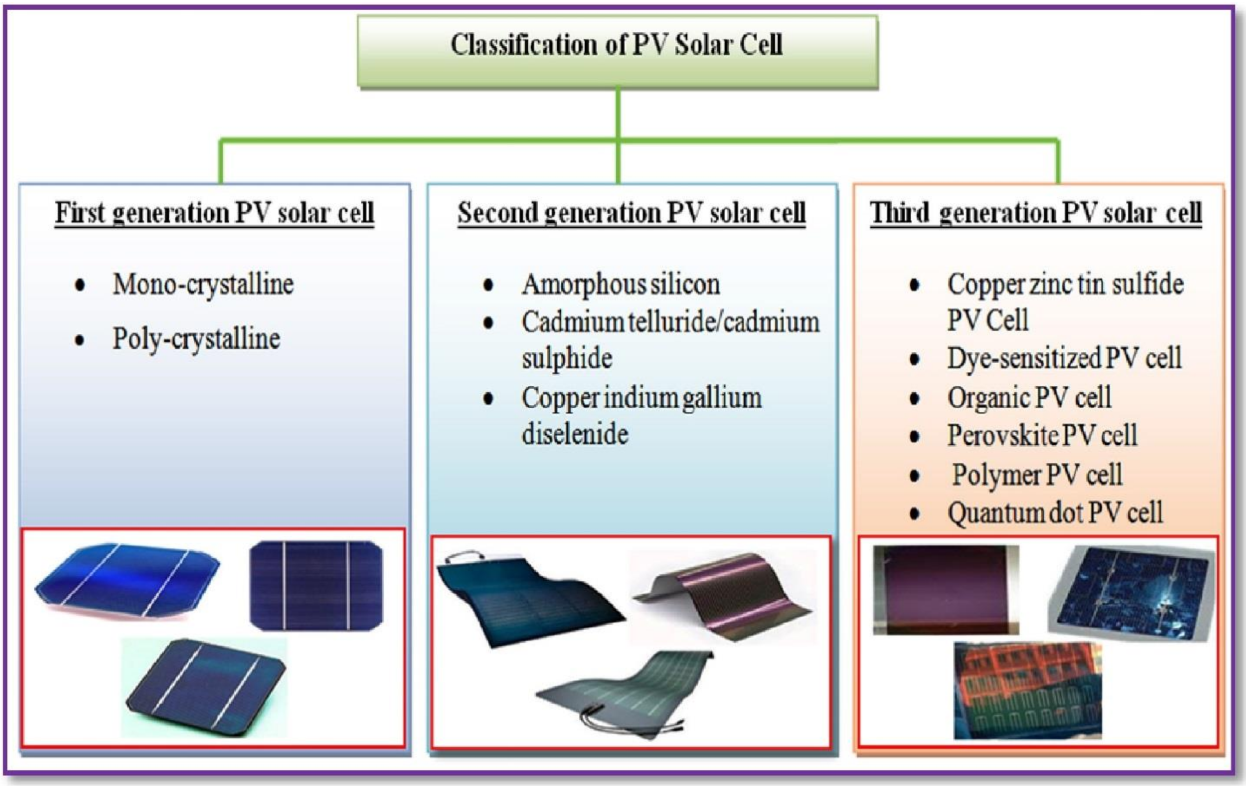


Figure 1-13 Classification of solar PV cells (Shukla et al., 2016).

4.2. Photovoltaic cells characteristics

The basic characteristics of a solar PV cell are the open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), Maximum output power (P_m), the fill factor (FF) and the solar energy conversion efficiency (η). Photovoltage and photocurrent values at open and short-circuit conditions are known as open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}), respectively. At short- and open-circuit operation conditions of a PV cell, the output power is equal to zero (Dittrich, 2018; Krauter, 2006; Mohanty and Tyagi, 2015). **Figure 1-14** shows schematically the (I–V) and (P-V) characteristic of a PV cell under illumination.

4.2.1. Short-circuit current (I_{SC})

The short-circuit current (I_{SC}) is a very essential parameter of a solar PV cell. It happens in an illuminated, short-circuited PV cell. In this condition (V=0).

4.2.2. Open-circuit voltage (V_{oc})

The open-circuit voltage (V_{OC}) describes the tension between the contacts in no current passing state (open circuit).

4.2.3. Maximum power (P_m)

The maximum output power (P_m) is the greatest possible power value of the PV cell and describes the maximum product of (I and V) values.

$$P_m = I_m \times V_m \qquad (1)$$

4.2.4. PV cell efficiency (η)

The conversion efficiency (η) of a solar PV cell is defined as the ratio between the maximum power (P_m) extracted by the PV cell and the product of (solar irradiation (G) and PV cell surface (A)) at which the PV cell is illuminated.

$$\eta = \frac{Pm}{(A \times G)} \qquad (2)$$

4.2.5. Fill factor (FF)

The fill factor (FF) is an additional parameter to characterise a PV cell quality; it expresses the ratio by which the (I_{SC}–V_{OC}) rectangle is filled by the (I_m–V_m) rectangle.

$$\text{FF} = \frac{Im \times Vm}{(Isc \times Voc)} \qquad (3)$$

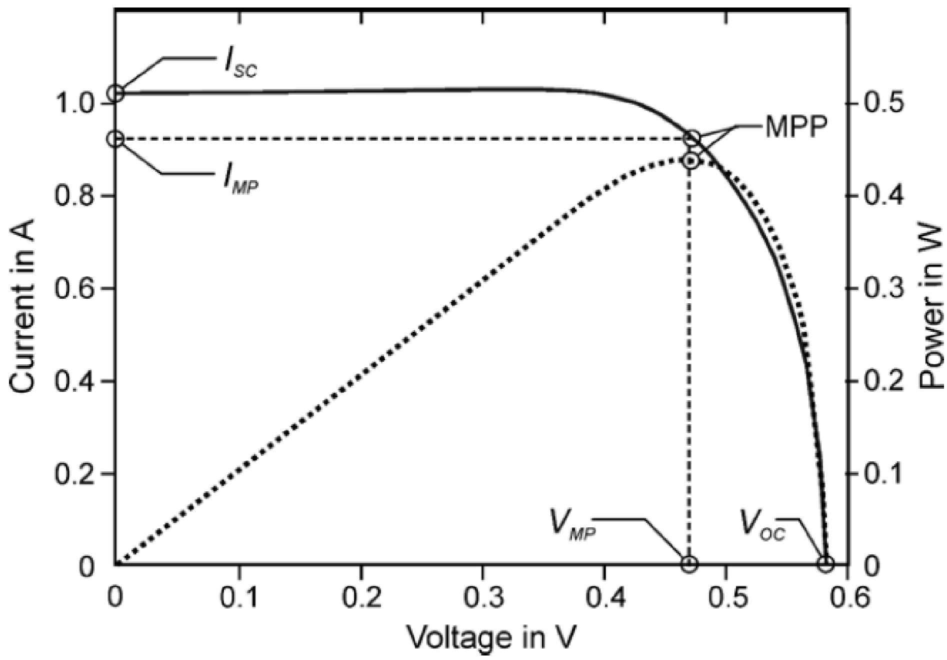


Figure 1-14 (I-V) and (P-V) characteristics of a PV cell (Krauter, 2006).

4.3. Photovoltaic applications

Photovoltaic solar energy applications are varied, and can be classified into two main groups:

- Autonomous systems (Isolated installations).
- Grid-connected systems (Installations connected to the network).

4.3.1. Autonomous systems

Autonomous PV systems are the systems known as "off-grid systems" that aim to cover energy demand from solar energy based on photovoltaic conversion, without the need to be connected to the electricity network. In most cases, these systems are used in isolated sites (Bayod-Rújula, 2019). Photovoltaic solar energy has been used in a variety of applications that can range from small calculators to artificial satellites. The main photovoltaic energy applications in autonomous systems can be classed into: buildings and homes electrification (BIPV), autonomous lighting, water pumping and treatment, agricultural applications, communications and many other specific applications (Qazi, 2017). **Figure 1-15** shows the different subsystems that existent in an autonomous photovoltaic system.

4.3.2. Grid-connected systems

Grid-connected PV systems known as "on-grid systems" is a type of installation including three principle elements: the photovoltaic panels, the (DC/AC) inverter, and the electricity line. In this type of systems, the power produced by the modules goes directly to a (DC/AC) inverter that converts the direct current into alternating current appropriate to inject the generated energy in the electrical network (BOUTLILIS Fatima, 2018; Khatib et al., 2016). **Figure 1-16** illustrates the principle of a photovoltaic system connected to the grid.

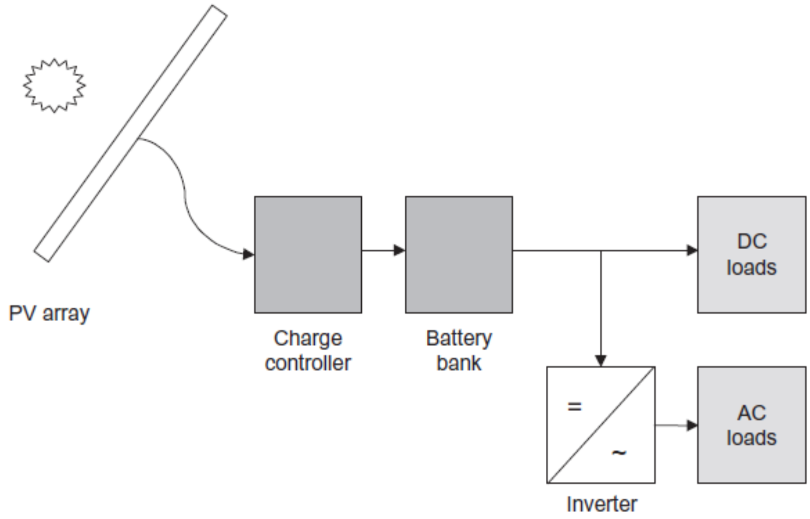


Figure 1-15 Schematic of a stand-alone PV system (Pearsall, 2017).

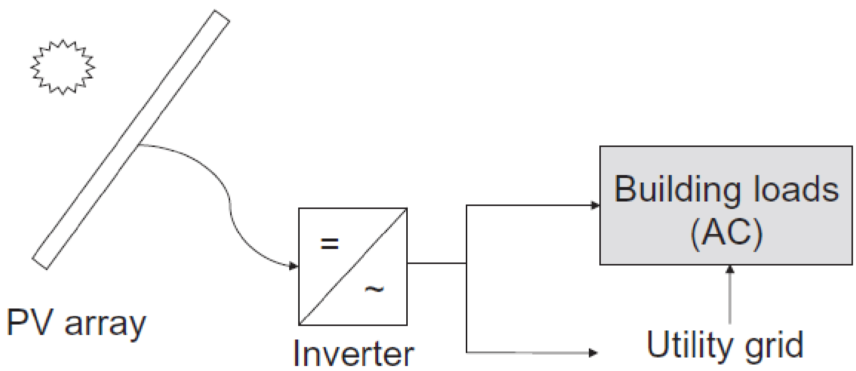


Figure 1-16 Schematic diagram of a grid connected PV system (Pearsall, 2017).

5. CONCLUSION

In this chapter, a brief overview on photovoltaic energy is presented. The global and national photovoltaic energy potential, installed capacities and electricity generation share were discussed, in addition to the main PV cell technologies, different PV cell parameters and photovoltaic energy applications. Photovoltaic energy showed the highest increase rate in electricity production share among all renewable energy sources due to the important price reduction of PV cell technologies. Algeria has a huge RES potential and it planned an ambitious program for renewable energies development. However, the implementation efforts are very slow.

Photovoltaic cell technologies are classified into three main generations, which are silicon based PV cells, thin-film PV cells and other new technologies such as organic and perovskite PV cells. The photovoltaic energy can be used in various applications and can be classed in two major groups, autonomous PV systems (such as buildings electrification and water pumping) and grid-connected PV systems.

1. INTRODUCTION

Various factors affect the PV systems conversion efficiency and the power produced from them. These factors can be classified and divided into three main sections, which are:

- Photovoltaic system factors such as (PV panel structure, PV material, PV panel efficiency and band-gap energy).
- PV installation factors such as (angle of inclination or orientation of PV panels, fixed or tracking mechanism and maximum power point tracker MPPT).
- Environmental factors such as (ambient temperature, solar irradiation, wind velocity, humidity and dust deposition).

Solar PV modules installed for energy generation are strongly influenced by weather conditions especially in arid and desert areas where the climatic conditions are harsh, which limited their conversion efficiency and reduce the life time cycle.

In this chapter, the effect of different climatic factors on PV systems performance is discussed apart to have a clear idea about the most affecting weather parameters on the efficiency of PV systems. The dust accumulation and temperature effect focused on more and have discussed in details because they have the most important degradation effect in arid and desert regions. The different cleaning and cooling methods and technologies for mitigating the impact of these parameters are also reviewed in this chapter.

2. INFLUENCE OF ENVIRONMENTAL FACTORS ON PV SYSTEMS PERFORMANCE

2.1. Effect of solar irradiation

Solar irradiation is the quantity of power received from solar sources per unit area. The solar irradiation hitting on a surface is divided to direct, diffused and reflected irradiations. Solar PV panels convert directly the solar light rays to electrical current based on the photovoltaic effect (Fouad et al., 2017). It is well known that the output power and conversion efficiency of a PV module are maximum under the STC (G=1000W/m^2, Ta=25°C, V=1.5m/s) conditions. However, the STC conditions cannot be provided continuously under real outdoor operating conditions where the PV systems installed actually. The solar irradiance intensity significantly varied with the environmental conditions, geographical location characteristics and daytime. Thus, an important variation in the PV system efficiency (Xiao et al., 2014). The reduction of the solar irradiation level below 1000 W/m^2 generally results in a dropping of the conversion efficiency depending on the PV cell technology (Parretta et al., 1998).

It is obvious from **Figure 2-1** that with the reduction of irradiance intensity, the short circuit current (Isc) decreases very sharply, while the open-circuit voltage (Voc) decreases slightly. Therefore, the PV cell output power decreases with the irradiance intensity decreasing (Xiao et al., 2014), as the solar irradiance intensity increases, the output power and the electrical current of the PV module increase too. Therefore, the output power and the current of PV module have approximately a linear relationship with the solar irradiance intensity (Hamrouni et al., 2008; Shahatha Salim et al., 2013).

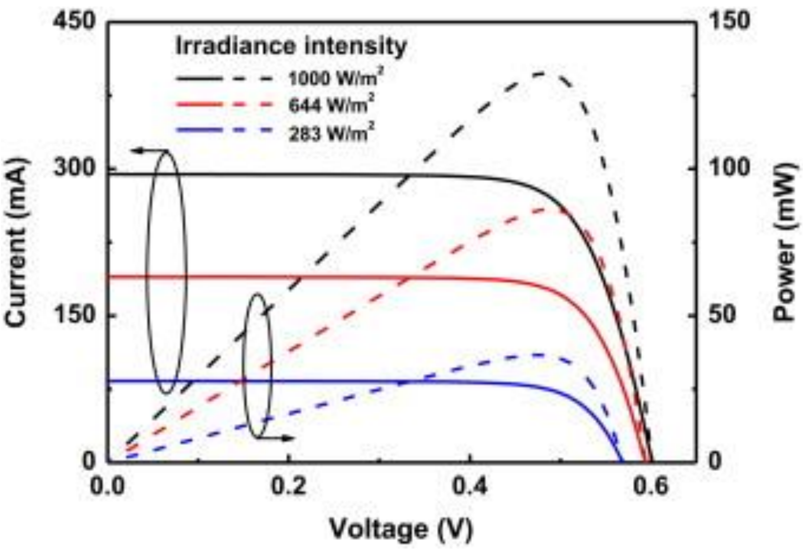


Figure 2-1 (I–V) and (P–V) characteristics of PV cell at 25°C under various irradiance intensities (Xiao et al., 2014).

2.2. Effect of shading

Complete or partial shading may be caused by nearby obstacles shadows (trees, buildings, antennas, and electricity poles), moving clouds, birds soiling and other shading types (Fathy, 2015). Since the power outputs of PV modules is directly proportional to the irradiance intensity, the reduction in the light due to a complete or partial shading of a PV cell can affect negatively on the electric productivity of the PV cell (Ubisse and Sebitosi, 2009). The decrease in the produced current of a cell leads to the current reduction of the entire string of PV cells connected in series resulting in a significant decrease of the whole PV panel performance (Ekpenyong, E.E and Anyasi, 2013; Torres et al., 2018; Wang et al., 2020).

(Bouraiou et al., 2015) studied experimentally the effect of partial shading on the output power and electrical characteristics of a PV module (12 × 6) cells. The experiment based on the shading of first row cells of the PV module from the first to the sixth cell. It was found that the output power losses increase with the shaded area of the PV module. The maximum power and efficiency decreased from 79.7 W, 10.87% (case no shaded cells) to 16.45 W, 1.89% (all first row cells are shaded) respectively, due to the effect of partial shading **Figure 2-2**.

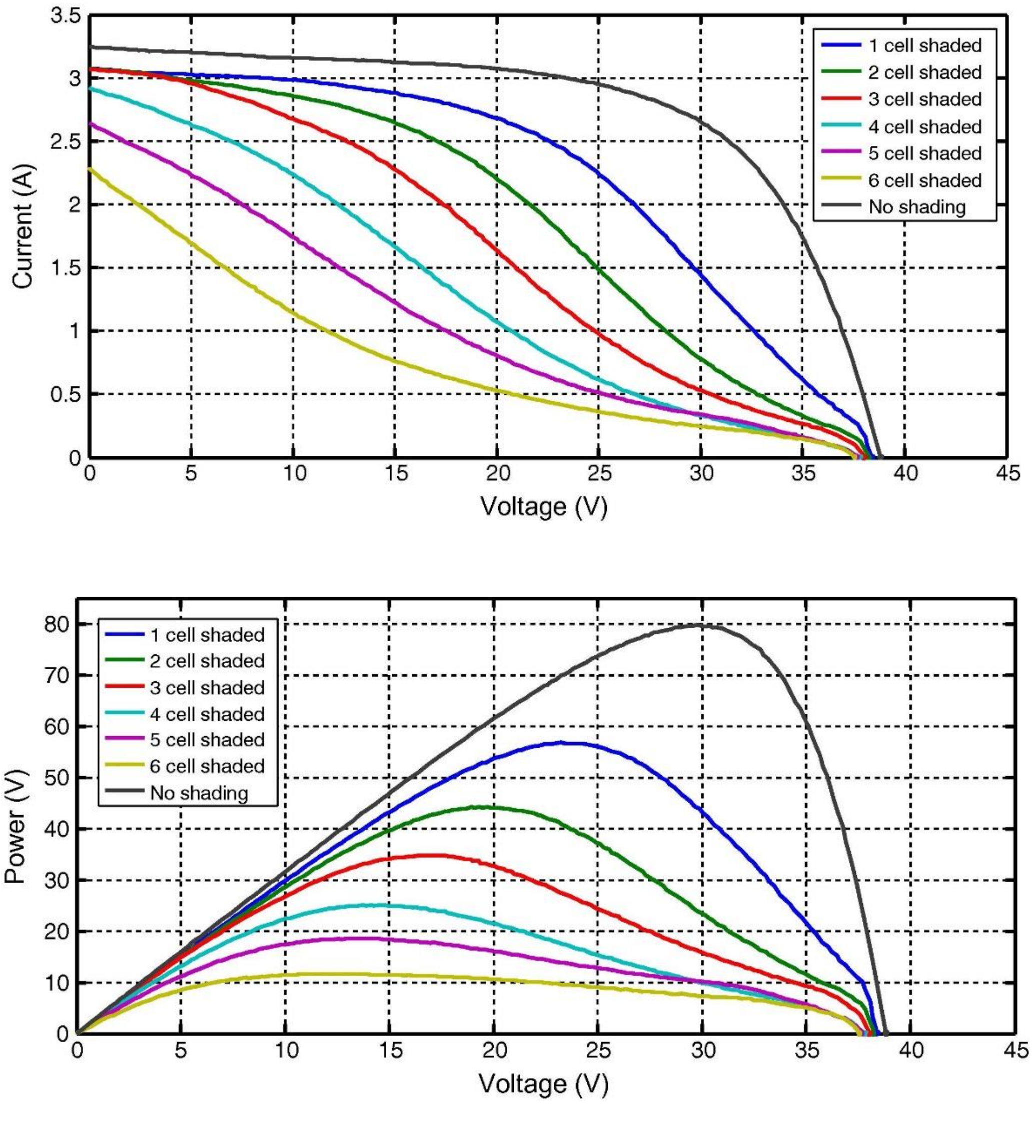


Figure 2-2 I-V and P-V curves of tested PV module under partial shading (Bouraiou et al., 2015).

In addition to the performance degradation of the PV systems, the partial shading can cause a permanent damage of the PV panels because of the created hot spots in the shaded cells. This happens when a partial area of the PV module is shaded, where the short circuit current becomes lower than the flowing current generated by the other lighted PV cells, giving rise to reverse biasing, thus the power generated by the other cells dissipated as heat. Consequently, the PV panel can be damaged due to the very high local temperature depending on the size of hot spot and reverse current (Moretón et al., 2015; Solheim et al., 2013).

To mitigate the effect of shading and avoiding the hotspots in PV systems, bypass diodes are installed in PV cells during the manufacturing process. The main purpose of bypass diodes is to prevent the electric current to flow through the shaded PV cell but through the bypass diode. Therefore, the PV panel will be protected from power losses due to the hotspots creation in the shaded PV areas (Fathy, 2015; Kreft et al., 2020; Moreira et al., 2021).

Considering a shaded photovoltaic module in a string of photovoltaic modules connected in series. The shaded PV module generates lower current in comparison to the unshaded modules. Thus, the total generated current of the string is equal to the generated current of the shaded PV module due to the series connection. The integrating of the bypass diode in the photovoltaic module is the key to limit this problem. The bypass diode bypasses the shaded PV module to make the output electrical current of the unshaded PV modules pass through it instead of passing through the shaded photovoltaic module **Figure 2-3 and Figure 2-4** (Teo et al., 2020).

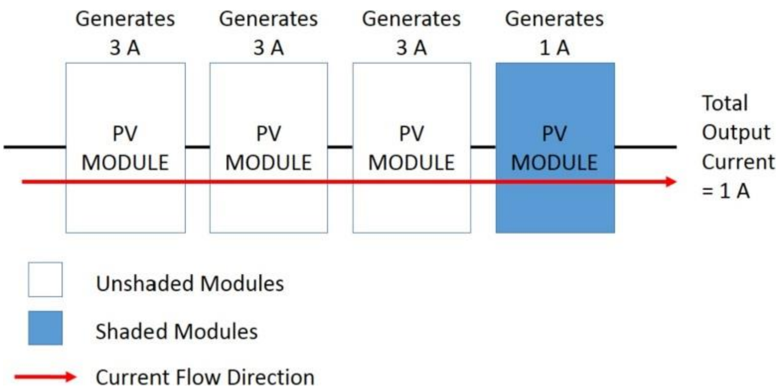


Figure 2-3 A photovoltaic string without bypass diodes.

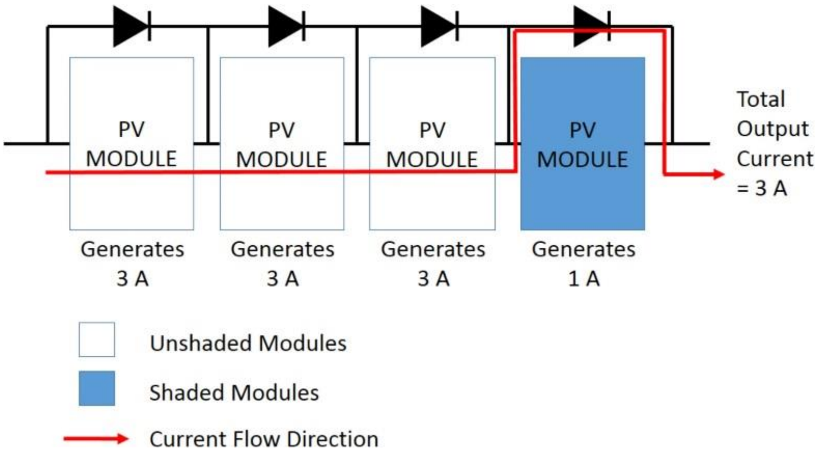


Figure 2-4 A photovoltaic string with bypass diodes.

2.3. Effect of dust deposition

Dust accumulation on the surface of PV modules is one of the major concerns, especially in arid and semi-arid areas where the climatic conditions are harsh and there are frequent sandstorms (Adinoyi and Said, 2013)**.** The deposition of dust on PV modules surface decreases the transmissivity of the glass cover, which leads to a significant reduction in the amount of solar irradiation received by the solar cells, resulting in a degradation in the power production performance of the solar PV modules (Babatunde et al., 2018; Guan et al., 2017). **Figure 2-5** shows a schematic of dust deposition effect on PV cells.

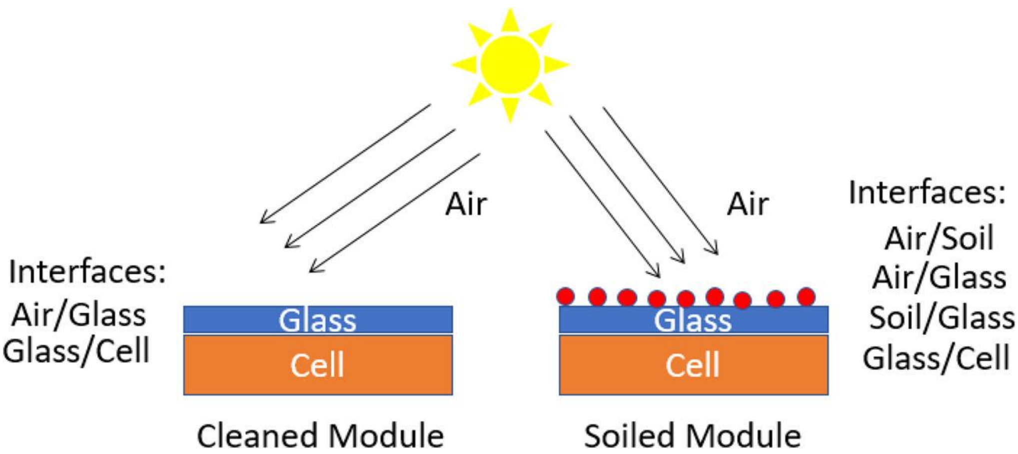
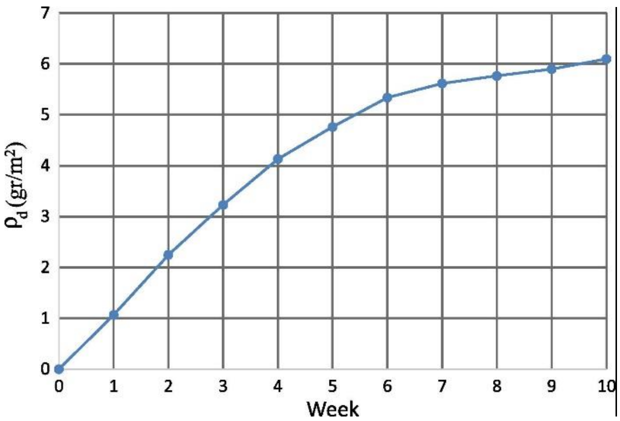


Figure 2-5 Effect of dust deposition.

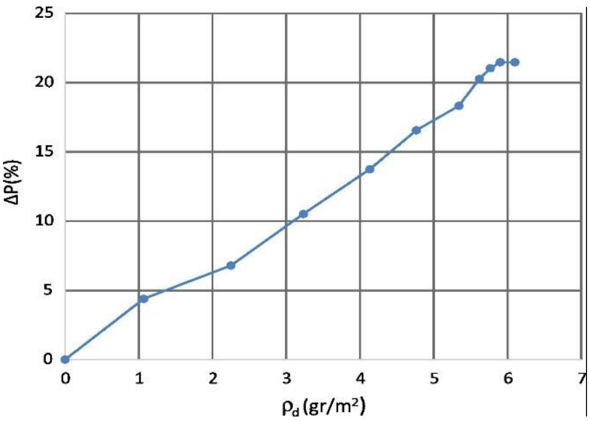
2.3.1. Region site and Exposure time

Typically, Photovoltaic panels are installed to work under outdoor environmental conditions. The more the PV panels exposed to outdoor weather conditions the more the accumulated dust mass on the PV surface, leading to significant power losses of PV systems. Several studies have been performed on the evaluation of dust accumulation effect. (Ramli et al., 2016) conducted an experimental investigation on the effect of dust accumulation on the performance of PV modules. In their study, the effect of dust was analysed after different durations of external exposure conditions in Surabaya, Indonesia. It was found that the accumulated dust during long exposure under outdoor conditions caused a significant decrease in PV output power. A similar study was conducted by (Gholami et al., 2018) in Tehran, Iran. Their study indicated that PV power losses increases with the exposure time due to the accumulated dust density rises, after being exposed outdoors for 70 days, in a dry period without rain, the power output dropped by 21.47% due to the deposition of 6.0986 g/m^2 of dust on the glass surface of the PV modules. (Saidan et al., 2016), in their experiments in Iraq, found that the efficiency of PV solar modules decreased by approximately 18.74% as a result of dust deposition on the module surface after one month of external exposure. Deposition of dust on the PV surface rises when the outdoor exposure duration increases resulting in significant output power losses of PV systems **Figure 2-6**.

However, the dust accumulation rate is also related strongly to the climatic conditions during the exposure time. Weather conditions such as humidity, wind speed, precipitations and dust events have a significant impact on dust deposition rate on PV modules.



(a)



(b)

Figure 2-6 (a) Average dust surface density versus time at the end of each week, (b) Power loss versus average dust density at the end of each week (Gholami et al., 2018).

2.3.2. Particle size

Most studies have found that smaller dust particles, which have a specific surface area, are distributed more uniformly, thus reducing the voids between particles that permit the passing of light rays. This causes a significant performance deterioration in PV modules compared to that caused by coarse particles of dust mass. (Appels et al., 2013). In their study concluded that the deposition of fine dust particles (2–10 μm) on the PV module surface have the highest reduction effect of receiving solar intensity by solar PV cells in comparison to the coarser dust particles. This due to the more uniform distribution of smaller dust particles on the surface of PV modules than larger particles, which decreases significantly the voids between the particles where the light can pass through (Sarver et al., 2013).

(El-Shobokshy and Hussein, 1993) have studied the effect of the physicochemical properties of dust particles on PV modules' performance. The effect of cement, carbon and three types of limestone was tested. Results showed that at the same surface mass density the PV output power dropped by 90% and 40% in the case of carbon (5 μm) and cement (10 μm), respectively. This because of the fact that cement particles have smaller median diameter than carbon particles. In another study, (Fathi et al., 2017) have tested the influence of several dust types on the light transmission through the dusty glass. Results confirmed that smaller particles have the strongest deterioration effect on the light transmission compared with larger dust particles **Table 2-1 and Figure 2-7.** Therefore, it can be said that for the same mass of dust, finer dust particles cause more important PV modules performance degradation than larger dust particles.

Table 2-1 Grain size versus the dust types.

Dust types	Ash	Cement	Gypsum	Soil	Sand	Salt (NaCl)
Measured grain sizes (μm)	9.696	10	18.332	128.466	230.50	3191

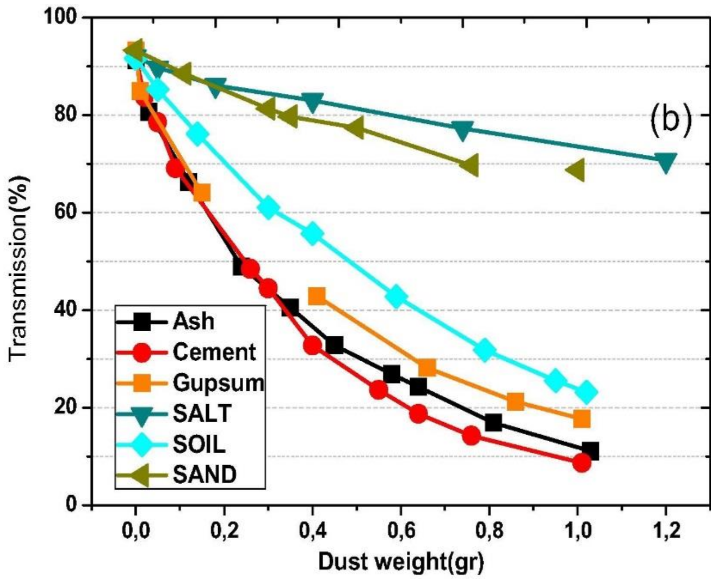


Figure 2-7 Transmission variations as a function of dust weight (Abderrezek and Fathi, 2017).

2.3.3. Inclination angle

Generally, photovoltaic modules are installed at a fixed tilt angle, which is the same of the location altitude. This in order to benefit as max as possible from the solar irradiation intensity over the year. However, the PV modules inclination angle has a significant influence on the deposited dust density on the top of PV modules. As the angle of inclination increases from the horizontal position (0°) to the vertical position (90°), the accumulated dust mass decreases (Appels et al., 2012; Hasan Ali AlBusairi; and Hans Joachim, 2010; Hee et al., 2012)**.** The increment of accumulated dust density decreases the transmittance of the PV glass cover leading to the reduction of the PV cell efficiency. (Elminir et al., 2006) Studied experimentally the effect of inclination angle on dust accumulation using 100 samples of glass. It was found that a dust amount of 15.84 g/m^2 was accumulated (for a tilt angle of 0°) compared to 4.48 g/m^2 (for a tilt angle of 90°) at the same conditions leading to transmittance dropping up to 52.54% and 12.38%, respectively. (Sayyah et al., 2014)**,** Observed that at different tilt angles of 0°, 15°, 30°, 45° and 60° after an exposure period of 38 days in the outdoor environment, the transmittance of glass plates reduced by 64%, 48%, 38%, 30% and 17%, respectively.

(Said and Walwil, 2014) in their study observed that the accumulated dust amount on the glass surface decreases with the increasing of the inclination angle leading to less dropping of the glass transmittance value **Figure 2-8 and Figure 2-9**. In general, raising of inclination angle encourages dust removal because of the gravity force. Therefore, the impact of inclination angle on the received solar irradiations and the dust deposition should be taken into account simultaneously to achieve an optimum tilt angle, which can attain the maximum solar irradiation values and lower dust deposition amount.

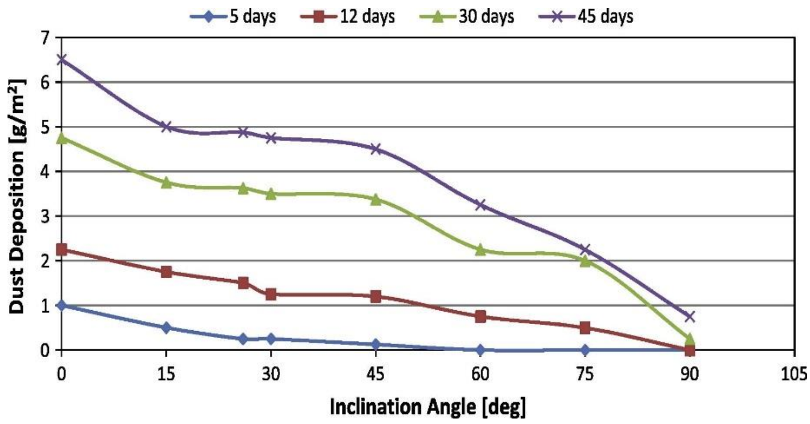


Figure 2-8 Dust Deposition with tilt angle for different exposure periods.

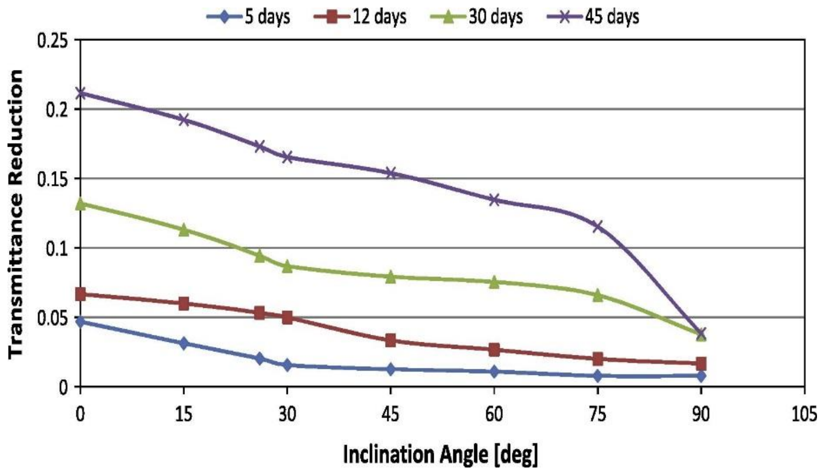


Figure 2-9 The transmittance reduction with tilt angle for different exposure periods.

2.3.4. Humidity

Humidity is the presence of water vapor particles in the surrounding air. Humidity can reduce the output power of PV modules due to the deviation of solar irradiation when the received light rays hit water particles (Mekhilef et al., 2012). Moreover, Humidity plays an important role in the dust deposition rate on the glass surface of PV modules because it encourages the dust adhesion forces by creating a sticky layer of dust on the glass surface

(Sayyah et al., 2014). This means that the dust deposition adhesion increases with humidity values due to the existence of condensed water between the glass surface and dust particles **Figure 2-10** (Gholami et al., 2018; Said and Walwil, 2014)**.** Therefore, the formed dust layer will be difficult to remove and needed extensive cleaning (Javed et al., 2017).

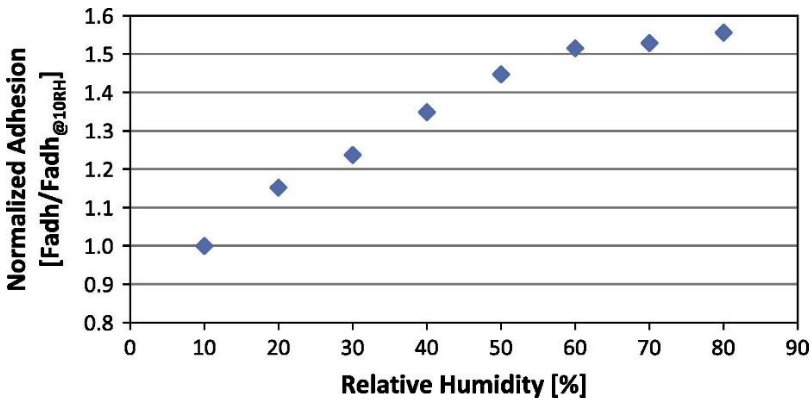


Figure 2-10 Effect of humidity on adhesion force (Said and Walwil, 2014).

2.4. Effect of temperature

Photovoltaic systems can convert only a small amount (5–25%) of incident solar insolation into electrical energy depending on the used PV cell technology, while the rest is transformed into heat. A part of the produced heat rises the PV module temperature itself while the remaining part is reflected back to the environment.

2.4.1. Electrical characteristics degradation

The increase in the temperature of PV cell leads to a significant decrease in the electrical efficiency and the output power of the module. The operating temperature has an adverse dependence on the cell conversion efficiency, if the operating temperature surpasses the standard operating temperature (usually 25 °C) (Kant et al., 2016; Shima et al., 2005).

High ambient temperatures and excessive solar radiation, especially in arid and hot regions can easily overheat the PV panels up to 75 °C, which causes a significant reduction in efficiency of about 25%. In crystalline silicon PV panels the efficiency drops by 0.5% with every 1 °C increase in operating temperature (Abd-Elhady et al., 2018; Ogbomo et al., 2018). In this context, numerous studies have been conducted for better understanding of the effect of temperature on the performance of PV systems. An investigation has been carried out by (Fesharaki et al., 2011) showed that the voltage and the module power output of the PV module are strongly affected by temperature variation. (Agroui, 2012) studied the performance of polycrystalline PV modules under different levels of solar irradiation (780 to 1250 W/m^2) and different values of operating temperature (61 to 75 °C). The results showed that under high operating temperature and high solar irradiation the modules lost about 18% of maximum output power compared to the results obtained in standard testing conditions.

In another study, (Najafi and Woodbury, 2013) have investigated numerically the generated power of PV cell under different values of temperatures and irradiance levels. Their results illustrated that under all irradiance levels the generated power decreased with the increasing of the cell temperature. At 3200 W/m^2, the generated power is higher by 80% for a PV cell at 25 °C compared to 87 °C cell temperature. In a similar study, (Jiang et al., 2012) have proved experimentally that the variations in operating cell temperature lead to major changes in output power of PV modules, at the same level of irradiance the performance of the modules drops with the cell temperature rises. The results showed that, the maximum output power of the module decreases from 227 W to 196 W under an irradiation of 1000 W/m^2 with an ambient temperature increase from (25 °C to 75 °C) **Figure 2-11.**

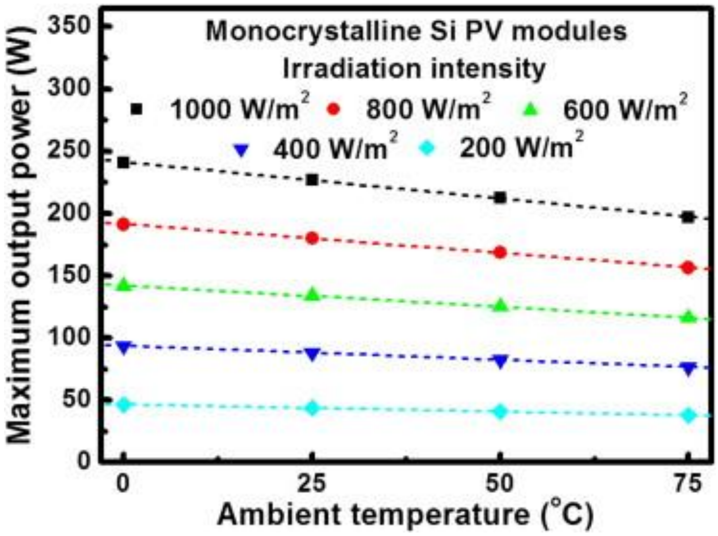


Figure 2-11 Maximum output power as a function of temperature under different irradiation intensities (Jiang et al., 2012).

Actually, polycrystalline and monocrystalline Silicon PV modules are the most technologies sensitive to high temperatures; the performance drop is about 0.4% to 0.5% for each 1 °C increase in the cell temperature. However, thin films PV cells (Amorphous-Si, CIGS and CdTe) are less affected by temperature rises; the performance drop is about 0.25% to 0.38% for each 1 °C increase in cell temperature **Figure 2-12** (David Tan, 2011)**.**

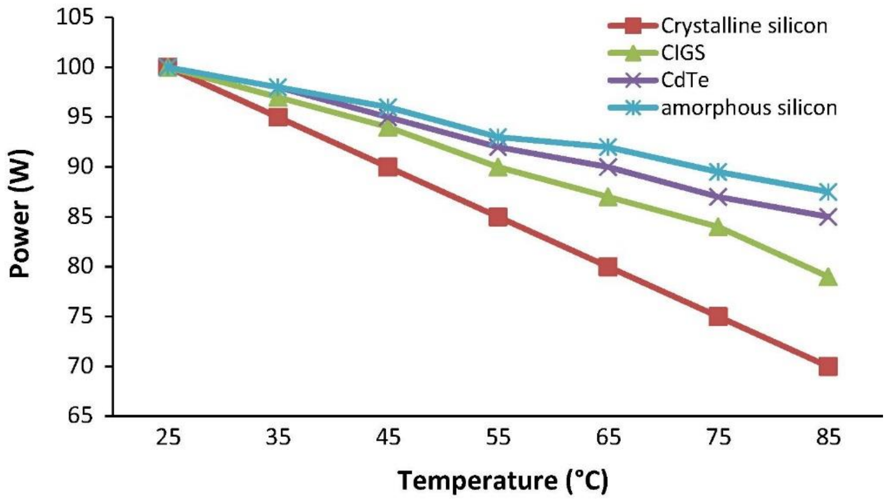


Figure 2-12 Temperature effect on various PV cell technologies.

2.4.2. Failure types

In addition to the efficiency degradation, high operating temperatures can cause severe vital damages on PV systems, which decrease their performance in a permanent way and lead to an important reduction in the lifetime service of the modules. (Köntges M. et al., 2014) determined the different failure types caused by high temperatures, failures such as delamination and back sheet adhesion loss are found in all PV modules types, while failures like burn marks, EVA discoloration, cell cracks, disconnected cell and string interconnect ribbons are found essentially in silicon based PV modules.

(Manganiello et al., 2015) reported that delamination, EVA discoloration, corrosion, bubbles and crack are the most aging mechanisms that occur in photovoltaic modules; these are mainly due to the harsh environmental conditions especially the combination of high temperatures and UV rays. (Tsanakas et al., 2016) studied and reviewed the characteristics of the most common fault types and degradation modes reported throughout the operational lifetime of operating PV modules. The authors defined that the optical degradation modes that includes encapsulates discoloration, bubbles, delamination and glass breakage occur mainly owing to the thermal stress (high operating temperatures).

(Bouraiou et al., 2015) investigated and evaluated the degradation of multicrystalline PV modules (UDTS 50) after a long-term exposure (11 years) under Saharan climatic conditions based on visual inspection and the I–V and P–V characteristics. They found out that EVA discoloration with different degrees and delamination are the most observed failure modes in the test field. Results showed that the performance degradation was 2.6%/year due to dark EVA discoloration and 1.18%/year due to delamination and light EVA discoloration.

Figure 2-13 shows defects such as degraded soldering and/or broken interconnecting ribbons (disconnected cells). A combination of failure types such as EVA discoloration, cracking of solar cells, busbar corrosion and delamination at the diagonal of PV cells are presented in **Figure 2-14.**

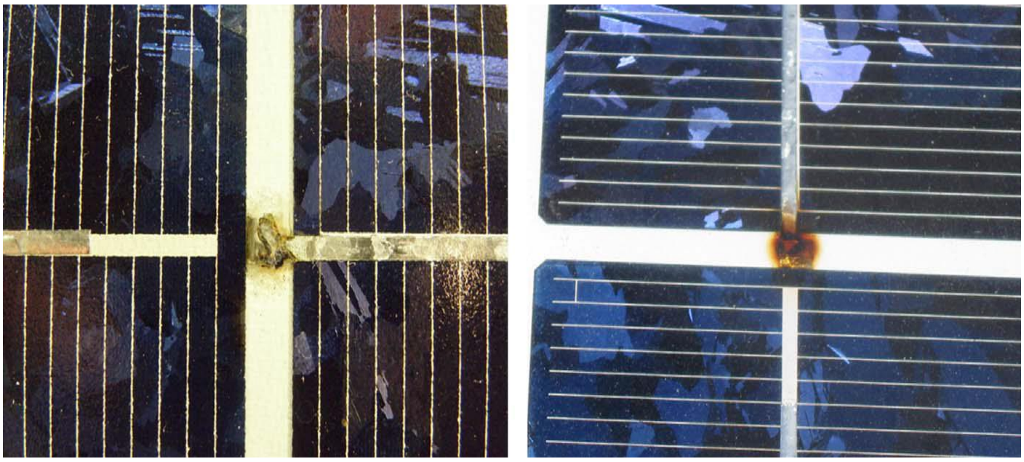


Figure 2-13 Degraded soldering and/or broken interconnecting ribbons (Tsanakas et al., 2016).

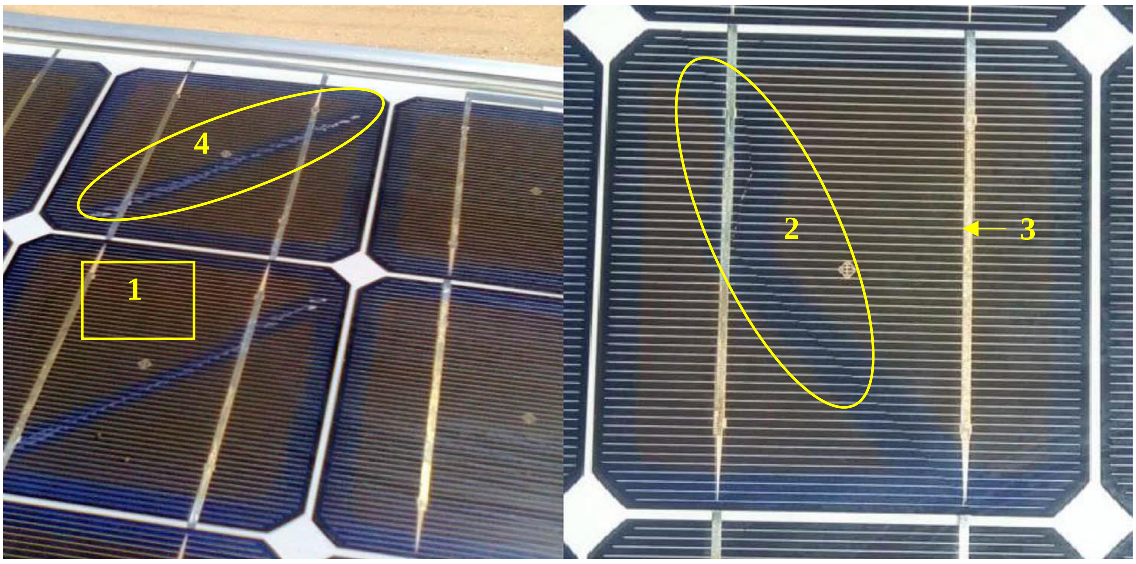


Figure 2-14 (1) EVA discoloration, (2) cracking of solar cells, (3) busbar corrosion and (4) delamination at the diagonal of PV cells (Bouraiou et al., 2018).

3. SOLUTIONS FOR PV EFFICIENCY ENHANCEMENT IN ARID AREAS

3.1. Cooling techniques

Most of operating PV systems are installed in arid and desert areas, which are characterised by harsh environmental conditions, especially the high ambient temperatures and UV radiations, which have a negative impact on the efficiency of PV modules and consequently the reliability and lifetime service. In this regard, many cooling techniques have been proposed and developed by researchers in order to reduce the operating temperature and improve the efficiency of PV modules. Cooling techniques of PV modules in general are divided into two main sections, passive and active (Hasanuzzaman et al., 2016)**.** Passive cooling systems are the systems that operate without any additional power source such as phase change materials (PCM), heat pipes, natural air ventilation, heat fins and natural water evaporation (Nižetić et al., 2017). On the contrary, active cooling systems are relying on pumps or fans, which require external power sources such as forced air ventilation, water spray over the front and/or back surfaces of the PV panel and forced water circulation (Nižetić et al., 2018; Sargunanathan et al., 2016).

3.1.1. Natural and forced air circulation

Among the different cooling approaches, natural air circulation is the simplest and a nonexpensive way for this purpose. However, due to the lower air thermal conductivity and volumetric heat capacity, the heat dissipation systems by natural air circulation are limited in their thermal performance. The role of fins attached to the back surface of the module is to extend the heat transfer area in order to augment the convection heat transfer (Nehari et al., 2016). A theoretical and experimental validation study has been conducted by (Amr et al., 2019) on the effect of passive cooling on the performance of a photovoltaic system based on the use of attached fins on the back surface of the module **Figure 2-15**. The results showed a reduction of the module temperature and an increase of the electrical efficiency due to fins cooling. It was also noticed that the increase in fins height and number resulted in a significant increase of the electrical efficiency of the module.

Fans can be added to these systems to get forced air circulation, which improves the performance of the cooling system. (Soliman et al., 2019) performed a laboratory experimental investigation on the use of a heat sink cooling system on the performance of the solar cells. This technique decreased the temperature of the cells by 5.4% and 11% with natural and forced air circulation, respectively. Moreover, the efficiency of the solar PV cell augmented by 8% and 16% with natural and forced air convection over the heat sink, respectively. (Mazón-Hernández et al., 2013). proposed and investigated experimentally natural and forced air circulation cooling of the backside surface of PV modules **Figure 2-16**. It was noticed that under the same operating conditions, the temperature reduction and the electrical output power improvement are better in the case with forced air convection compared to the natural air convection case.

Figure 2-15 Natural air circulation with fins cooling technique (Amr et al., 2019).

(a) Natural convection circulation. (b) Forced convection circulation.

Figure 2-16 Experimental setup for air based cooling technique (Mazón-Hernández et al., 2013).

3.1.2. Cooling using phase change Materials (PCMs)

PCM is a latent heat storage material, because it stores heat during the melting process. The PCM phase changing from solid to liquid occurs when the temperature increases. As the phase change is an endothermic process, the heat is absorbed by PCM. The material melting starts when the heat stored in the PCM material reaches the phase-change temperature, and then the temperature stabilises until the melting process is completed. Recently, many researchers focused on the integration of phase change materials on the rear surface of PV module for the thermal regulation in order to improve its efficiency. PCM are considered as an effective solution for PV cells cooling. Moreover, the stored heat could be used in other applications. (Huang et al., 2006) evaluated experimentally the thermal control of PV modules using PCM. The main obtained results showed that a combined use of PCM RT25 with internal fins resulted in a significant reduction in the temperature of the module and thus an important increase of the electrical efficiency. (Mahamudul et al., 2016) performed a study on the thermal regulation of a PV module by the integration of PCM based on numerical analysis and experimental investigation under Malaysian climate conditions. Results showed that a 0.02 m width of PCM RT35 reduced the temperature of the module by about 10 °C, which led to an increase in the efficiency. (Chandel and Agarwal, 2017) reported a literature review paper on using PCMs for photovoltaic cooling techniques including PV-thermal systems (PVT) and building integrated photovoltaic systems (BIPV). They concluded that although the satisfactory results of using PCM for the cooling of PV modules, the PCM is not the most preferred cooling solution because these techniques need further improvements in both technical and economical views. In addition, the suitability of PCM cooling techniques depends strongly on the location's geographical and climatic conditions. **Figure 2-17.** displays the integration of a PCM layer on the backside of the PV module for cooling.

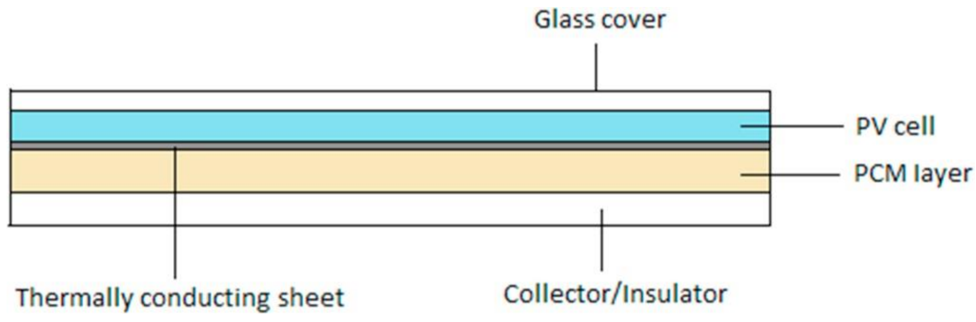


Figure 2-17 Integration of PCM layer on backside of PV module (Chandel and Agarwal, 2017).

3.1.3. Water cooling

Actually, Water have a high thermal conductivity and high heat carrying capacity compared to air. Consequently, several studies and research papers have focused on using water for the cooling of PV modules as water has a somewhat high thermal capacity and is capable of removing huge amounts of heat. An early experimental study carried out by (Krauter, 2004) on the effect of using a thin film of water flowing over the front surface of the PV module. The results displayed that the water stream decreased the cell temperature by 22 °C and thus the electrical energy yield increased by 10.3% **Figure 2-18**.

In order to improve the performance of a PV pumping system (Abdolzadeh and Ameri, 2009) conducted a water cooling system based on water spray on the front surface of the cells. Experimental results indicated that due to the use of this approach, the mean PV cell efficiency and total efficiency, increased by 3.26% and 1.35%, respectively, the mean flow rate was about 644 L/h during the test day compared to 479 L/h without a cooling system. (Bahaidarah et al., 2013) investigated experimentally an active water cooling system to enhance the performance of the PV modules in hot climate by attaching a solar thermal collector on the back surface of the module. They found that the use of a back cooling system dropped the module temperature by about 20%, consequently the electrical efficiency rose by 9%.

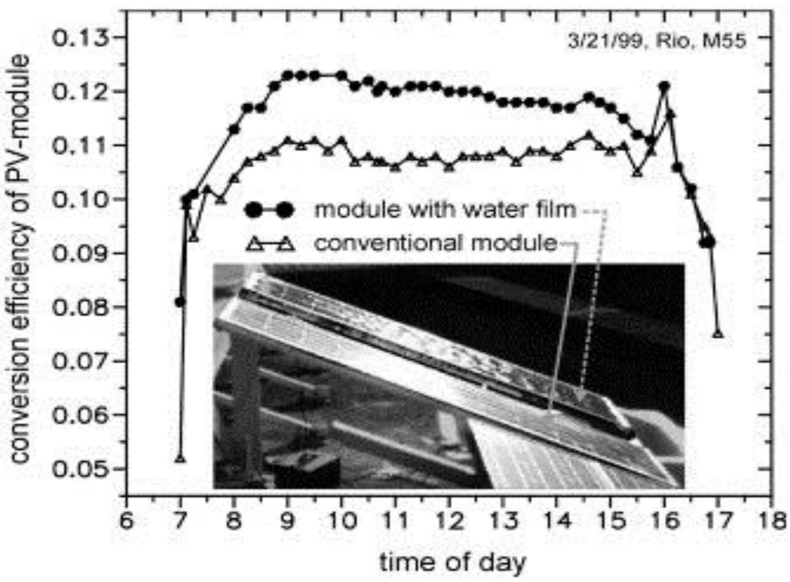


Figure 2-18 Cooling using a water film on the front surface of PV module (Krauter, 2004).

(Nižetić et al., 2016) proposed and experimentally tested an alternative cooling technique for PV panels based on the water spray on both the front and the rear surfaces of the module simultaneously **Figure 2-19**. Results showed the feasibility of this cooling technique which permitted to reduce the panel temperature from 54 °C to 24 °C and increase the output power and the electrical efficiency of the PV panel by 16.3% and 14.1%, respectively. Passive cooling by water evaporation presented attractive cooling results and can be considered as a promising answer for PV cells thermal regulation. However, a limited number of studies have focused on the use of this method as a cooling solution. (Chandrasekar et al., 2013) proposed a passive cooling system for PV panels by adding circular cotton wicks to the backside of the photovoltaic module; three different fluids, water, CuO/water nanofluid and Al2O3/water nanofluid were utilised as coolant in combination with cotton wicks for the proposed cooling system. Experimental results showed that the best results were obtained with water, with a reduction in the module temperature by 20 °C. Nano fluids (Al2O3 / water) and (CuO / water) contributed in the cooling of panels but with lower values compared with water. In another similar study, (Chandrasekar and Senthilkumar, 2015) developed a passive cooling system by attaching heat spreaders in conjunction with cotton wicks on the rear of the PV module, water was used as a coolant. It was found that the used cooling system aided in reducing the module temperature by 12% and increased the electrical yield by 14%. (Haidar et al., 2018) performed and investigated experimentally an evaporative cooling system. Results showed a significant reduction in the panel temperature by about 20 °C and an increase by about 14% of the electrical efficiency due to the using of the cooling system.

Figure 2-19 The front and backside cooling of PV panel by water spray system (Nižetić et al., 2016).

3.1.4. Thermoelectric cooling

Thermoelectric cooling is an innovative cooling technology, which has attracted much interest for thermal management of PV panels, it is usually used in electronics cooling applications and based on the Peltier effect (Kane et al., 2017; Twaha et al., 2016). Thermoelectric is a reliable and durable cooling technique for electronic components. However, it is not effective for high-power-dissipating electrical components. **Figure 2-20** shows an overall schematic of a combined TEC and PV system.

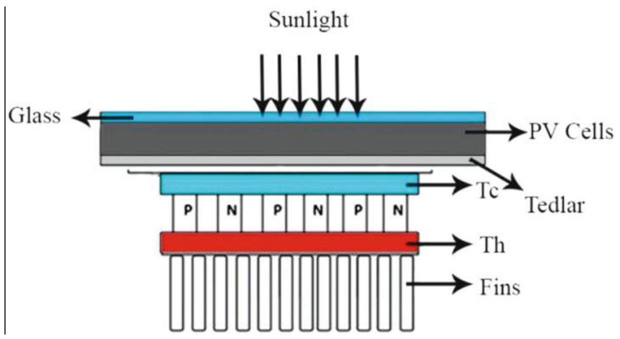


Figure 2-20 A schematic of hybrid PV cells combined with TEC modules (Moshfegh et al., 2018)

3.1.5. Radiative cooling

Radiative cooling is a simple technique for PV cells thermal management. This passive cooling method aims to enhance the radiative cooling effect by the improving of the mid-infrared (i.e., > 4 μm) thermal emissivity of the cells. However, this method showed a small cooling effect and still cannot be considered as an effective solution for PV cells cooling (Sato and Yamada, 2019; Zhao et al., 2018). The schematic diagram of radiative cooling method is shown on **Figure 2-21**.

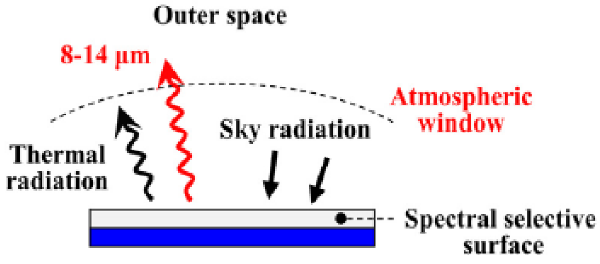


Figure 2-21 Schematic diagram of radiative cooling method (Sato and Yamada, 2019).

3.2. Cleaning techniques

Dust accumulation on the surface of PV modules results in lower performance and daily energy losses due to the decrease in glass cover transmittance. These losses in energy output are significant in large PV farms especially in arid and desert areas. Consequently, several studies have been conducted to find effective solutions to mitigate the impact of dust deposition on PV solar panels.

The different cleaning methods classification is shown in **Figure 2-22**. cleaning techniques can be divided in two sections, the first one is the traditional cleaning way manually by labour, and the second one is the self-cleaning either naturally by rainfall or by adding a self-cleaning feature such as super hydrophobic and super hydrophilic surfaces, electrodynamics screen, water cleaning and mechanical cleaning (Jamil et al., 2017).

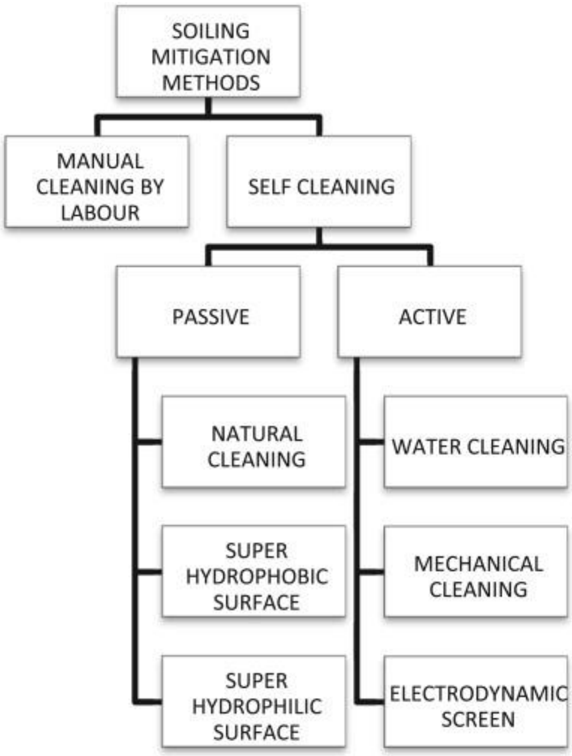


Figure 2-22 Classification of soiling mitigation methods (Jamil et al., 2017).

3.2.1. Natural cleaning

Natural cleaning of PV panels is often done by the falling rainwater. This cleaning way is effective for PV systems installed in environments with high precipitation rate. PV modules are usually inclined at a fixed tilt angle, which helps in the natural cleaning process by rain due to the gravity force. (Zorrilla-Casanova et al., 2011) found that rainfall lower than 1 mm was capable to remove dust from PV panel surface. Results also showed that rainfall cleaned effectively and reduces the PV performance losses to less than 4.4% compared to 20% of PV performance losses due to dust in dry seasons.

(Tanesab et al., 2015) suggested that natural cleaning by rain is an effective and low cost solution to mitigate the dust deposition on PV modules. However, light rainfall and dusty rain can lead to the production of a sticky layer of dust on the PV panel surface, which is hard to remove and needs expensive cleaning. (Hasan Ali AlBusairi; and Hans Joachim, 2010; Smith et al., 2013) found that rainfall was able to restore a low (only 1%) PV performance of the panel cleaned manually after a decrease of 4% due to the dust deposition. Therefore, it could be said that natural cleaning by rainfall does not contribute in the mitigation of PV performance degradation due to the accumulation of dust in arid and Saharan areas, as the rain precipitations are very rare.

3.2.2. Manual cleaning

Manual cleaning is one of the primitive and easiest methods for PV modules cleaning, which is based on the using of water and soft brushes or wipers to avoid scratching the cleaned surface. This method can clean efficiently by labour the hard soilings (bird droppings and cemented dust) of PV modules. However, this cleaning way has some disadvantages such as the huge water quantity requirement and the high cost of labour, especially in power plants that installed in harsh arid environments (Al-Jawah, 2014).

3.2.3. Water cleaning

It is a common cleaning way where water is used as the main cleaning agent. Uncompressed water cleaning methods are low effective and have the same principle of the rainfall cleaning way, which cannot remove hard soilings from the PV panel surface (Appels et al., 2013). In some methods, pumps can be used to provide compressed water, which aide in difficult dust particles removing. However, this method has many disadvantages such as huge water quantity loss and the high electricity consumption due to the using of pressure water pumps. Moreover, some special cleaning materials can be mixed with water to have more effective cleaning.

A study performed by (Moharram et al., 2013), reports that combining water with a surfactant is used to enhance the cleaning of difficult soiling. Nevertheless, brushing is necessary in water cleaning methods due to the possibility of luring more dust particles to deposit on the PV panel surface after cleaning while it left wet to dry (Kazem et al., 2020). (Massi Pavan et al., 2011), in their research, compared the cleaning of PV panels using pressurised distilled water with and without brushing after water cleaning. It was found that brushing after water cleaning improves the output power by 6.9% compared to only 1.1% improvement without brushing, this mainly due to that fine dust particles are much adhered and can be removed only by brushing.

3.2.4. Mechanical and robotic cleaning systems

Many mechanical devices and automated robots with various designs have been developed for PV modules cleaning in order to maximise their efficiency and minimise the cleaning cost and water consumption (Yuyi et al., 2013; Zhen and Yang, 2012). These systems use brushes or wipers with horizontal or vertical movement and sometimes combined with water (Lamont and El Chaar, 2011). Robotic cleaning systems are stable and reliable and have many advantages such as automatic, quick response and low water consumption. However, this technique effectiveness is limited and has some disadvantages especially the high initial investment cost, required maintenance and power consumption (Jamil et al., 2017).

3.2.5. Electrodynamics screen (EDS)

Electrodynamic screen is a simple self-cleaning technique for PV modules without the need of water or any external mechanisms (Mazumder et al., 2013). This technique based on the using of a high voltage supply electric field, an electric wave will be created on the screen. Dust particles might have negative or positive charges, which will make them move accordingly to the electric wave until they pushed out at the end of the screen surface **Figure 2-23**. This cleaning method is characterised by its simplicity, fast cleaning and low power consumption. However, it also has some disadvantages especially the risk of screen degradation under high ultraviolet irradiation, it works well with dry and large dust particles and less effective with wet and fine particles (Johnson et al., 2005).

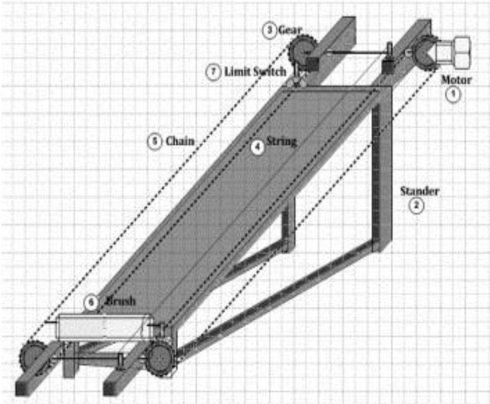
A recent field study of EDS prototypes carried out by (Guo et al., 2019) found that the efficiency of dust removal using EDS diminished with the increment of stayed time of dust particles on the EDS surface. This is mainly due to the humidity variation, which increases the particle adhesion force and leads to electrostatic charge decay (Javed and Guo, 2020).

3.2.6. Superhydrophobic and Superhydrophilic surfaces

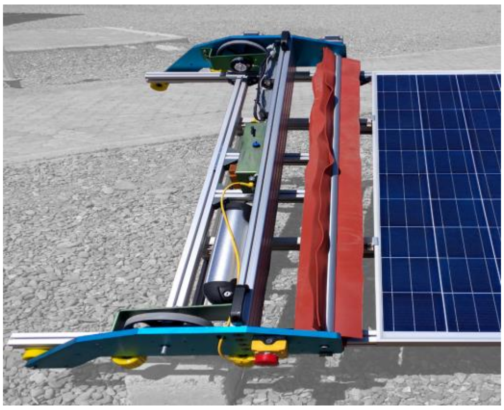
Super hydrophobic surface is an anti-soiling coating surface, which is characterised by low wettability and high water droplet movability properties. While, the superhydrophilic surface anti-soiling coating surface is characterised by a strong water attraction property (Gupta et al., 2019). The PV module self-cleaning effect can be provided by improving the PV glass cover property with the laying of superhydrophobic or superhydrophilic surfaces. This method reduces the accumulated soiling rate in atmospheric conditions and facilitates the detachment of deposited dust particles with rain falling water or water cleaning systems, which contributes in the reduction of used water amounts (Strauss et al., 2019; Zhang et al., 2019). However, more investigations required about the effectiveness and reliability of this cleaning method under different environmental conditions (Park et al., 2011). In addition, this technique needs using water for dust particles removing, which made it not a promising solution in dry environments where rainfall is rare and scarce water sources taking into account the possibility of surface degradation due to the high UV irradiation.

(a) Manual cleaning (Ilse et al., 2019)

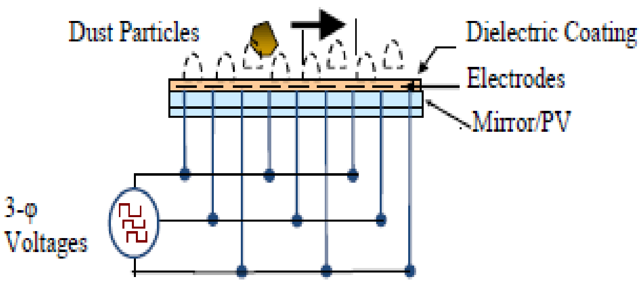
(b) Water cleaning (Jain-Spark)



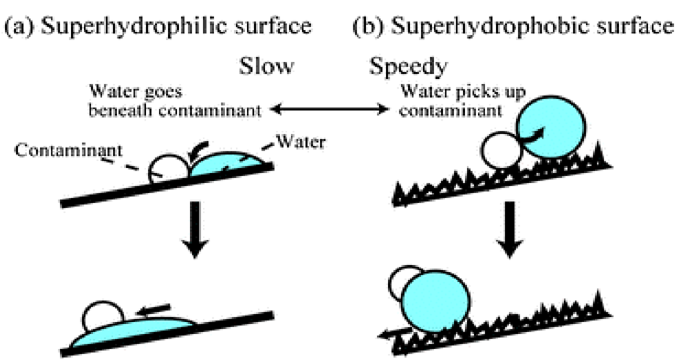
(c) Electromechanical cleaning system (Lamont and El Chaar, 2011)



(d) Automatic cleaned PV (Parrott et al., 2018)



(e) The working conceptual of EDS (Morales et al., 2017).



(f) Self-cleaning of super hydrophilic surface versus super hydrophobic surface (Nishimoto and Bhushan, 2013).

Figure 2-23 Different cleaning methods for photovoltaic modules.

4. CONCLUSION

A review study on different environmental factors effect on the PV cells performance has been presented in this chapter. It can be concluded that climatic conditions such as irradiance intensity, dust deposition and ambient temperature have a major impact on the PV system conversion efficiency. Dust deposition and high ambient temperatures are the most influencing factors on PV systems installed in arid and desert areas. Where the PV conversion efficiency is inversely dependent to the operating temperature and deposited dust density. High operating temperatures lead to a significant diminishment of PV cells efficiency and may lead to permanent damage of the PV cells limiting their lifetime cycle. Dust accumulation is also responsible in the reduction of PV cells performance, the deposited dust density is related mainly to the geographical location, environmental conditions and tilt angle, where the more deposited dust density causes more power losses. Several available techniques to mitigate the impact of these two parameters have also been reviewed in this chapter. Water based cooling and cleaning methods have shown the most promising improvements among all the reviewed solutions. However, water sources scarcity creates a big challenge against these techniques. PCMs based cooling solutions also showed interesting results, but this method needs more improvements in the economical aspect. Manual and robotic cleaning are the most used techniques for PV systems. However, as the dust type and density are different from region to another, each region will have a special cleaning method based on the techno-economical analysis.

CHAPTER 3 EXPERIMENTAL STUDY OF DUST ACCUMULATION EFFECT ON THE PERFORMANCE OF PHOTOVOLTAIC MODULES

1. INTRODUCTION

Dust accumulation on the surface of PV modules results in lower performance and daily energy losses due to the decrease in glass cover transmittance. These losses in energy output are significant in large PV farms especially in arid and desert areas. The main aim of this chapter is to investigate the output power losses due to dust deposition on glass cover surfaces of PV modules installed in arid and desert environments. In the present chapter the effect of solar irradiation, dust accumulation and natural cleaning (rainfall) were assessed experimentally, based on performance evaluation of crystalline photovoltaic modules installed at the LENREZA laboratory in Ouargla University, South of Algeria. In addition, the effect of sandstorms on the performance of a 30 MW grid-connected PV power plant installed in the same area was evaluated before, during, and after a sandstorm day. The accumulated dust was collected and analysed using an XRF Spectrometer.

2. PRESENTATION OF THE TEST REGION

The experiments were conducted under outdoor conditions at the laboratory of New and Renewable Energy in Arid and Saharan Zones – LENREZA, Ouargla University, Algeria, and at the grid-connected PV power plant (SKTM El-Hadjira, Ouargla). The city of Ouargla is situated in the Southeast of Algeria and covers a total area of about 163,233 km^2. It is located at an altitude of 164 m, latitude of 31° 57' N, and longitude of 5° 21' E. Ouargla is one of the warmest regions in Algeria (and in the world). It has a Saharan type of climate, which is characterised by low temperatures in winter, very high temperatures in summer, low atmospheric humidity, low rainfall, and an average annual wind speed of 3.70 m/s. There is considerable sunshine in Ouargla, as there are approximately 138 clear-sky days per year. On the other hand, Ouargla is also characterised by the frequent occurrence of sandstorms, especially in the spring period from February to May (ONM). It also has one of the highest mean annual solar radiation values globally. The PV power potential of both Algeria and the Ouargla region (Solargis) is illustrated in **Figure 3-1**.

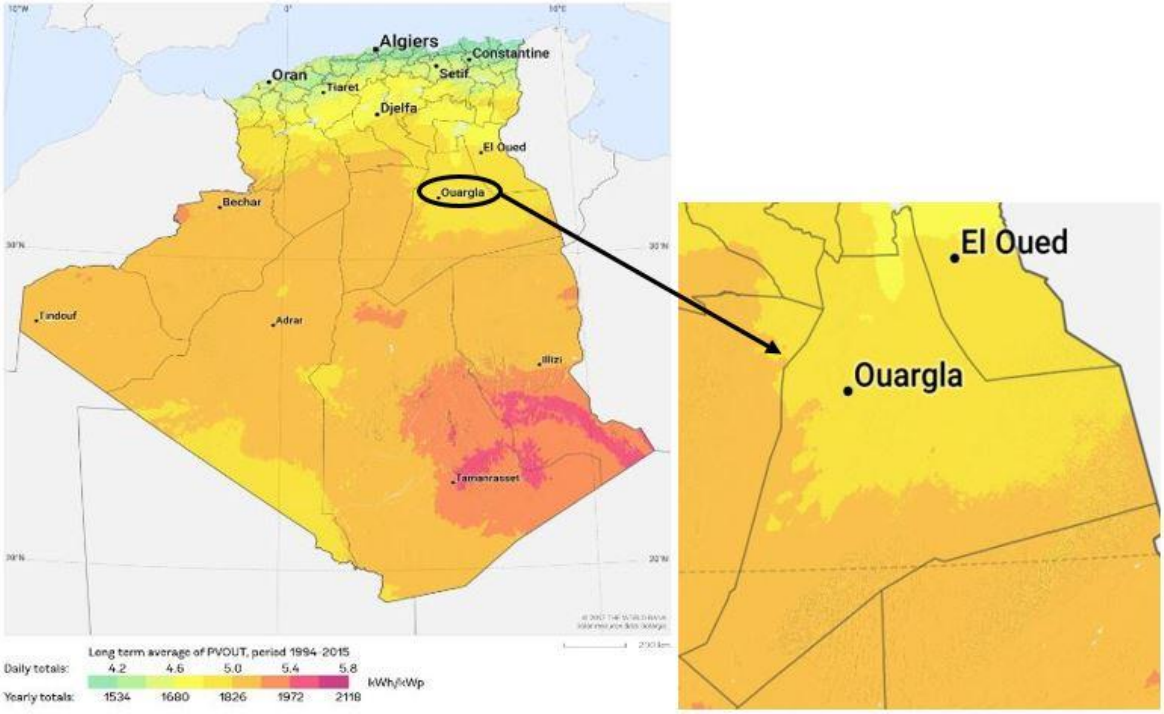


Figure 3-1 PV power potential of Algeria and Ouargla region (Solargis).

3. EXPERIMENTAL SETUP

3.1. Test details

The experiments to evaluate the dust deposition effect were conducted from 15 May 2018 until 10 July 2018 (8 weeks). Two monocrystalline PV solar modules of type SYP80S-M (80W) were used. One module was taken as a reference, and cleaned regularly at the beginning of each measurement using a soft wiper and distilled water, while the other was left without cleaning to study the effect of dust accumulation on output power of the solar panels. Both PV modules were oriented to the south with a fixed tilt angle of the latitude 31º 57’ for the location of Ouargla city, Southeast of Algeria. The photographs of dusty and reference (clean) modules are shown in **Figure 3-2**. The electrical specifications of the SYP80S-M monocrystalline PV solar module under standard test conditions (STC) are displayed in **Table 3-1**.

The experimental setup consisted of a variable resistor (PHYWE SE6, accuracy ±10%) considered as a load resistor and digital multi-meters (METEX ME-31, voltage accuracy

±0.5%, current accuracy ±2%) for measuring the power output in terms of current and voltage, as shown in **Figure 3-3** . A K-type thermocouple (accuracy ±2%), placed in a special container, was used to measure the ambient temperature. Solar irradiation was measured using an LP02 pyranometer (accuracy ±1.8%). The ambient temperature, solar irradiation and electrical characteristics of both the reference (clean) and the test (dusty) modules were monitored and recorded every 30 min under outdoor climatic conditions from 08:30 to 16:30 local time during a sunny day (July 10, 2018).

(a) Dusty module (b) Clean module

Figure 3-2 Photograph of clean and dusty PV modules.

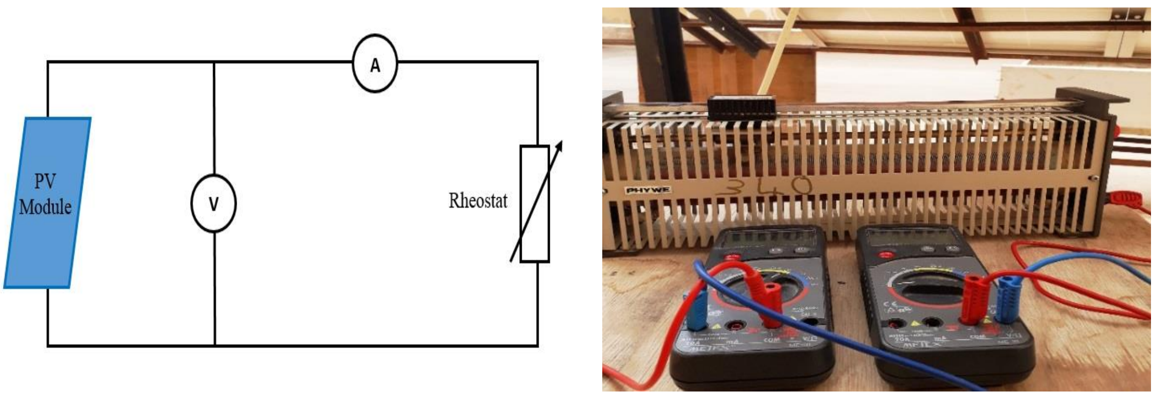


Figure 3-3 Electrical circuit measurements.

Table 3-1 Technical specifications of the SYP80S-M PV module under STC.

Parameter	**Specification**
Technology	Monocrystalline
Maximum power (W)	80
Maximum voltage (V)	17.2
Maximum current (A)	4.65
Open circuit voltage (V)	21.6
Short circuit current (A)	5
Area (mm^2)	1195 × 541

3.2. Dust density measurements

A piece of transparent window glass (10 cm × 10 cm) and 3 mm thickness was used as a sample to measure the amount of accumulated dust on the panel's surface. The glass sample was mounted with the same orientation and tilt angle as that of the studied modules. The accumulated dust on the surface of the glass piece was carefully weighed using a (DENEVER SI-114) balance with an accuracy of 0.1 mg. The weight of the deposited dust was calculated as the difference between the mass of dusty glass and clean glass. The weight of dust was divided by the area of the glass piece to obtain the density of accumulated dust on the glass surface. **Figure 3-4** shows the experimental setup of dust density measurements.

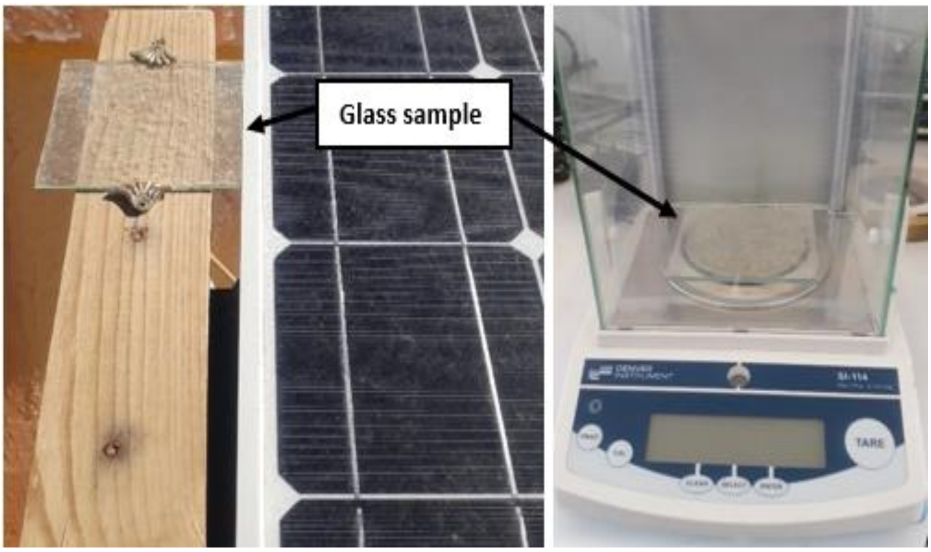


Figure 3-4 Dust density measurements.

3.3. Presentation of (SKTM) grid-connected PV power plant

The grid-connected PV power plant is located in El-Hadjira, Ouargla, South of Algeria. It covers a total area of 60 ha, has 30 MW of installed capacity, and is connected to the 60 kV national grid network. The power plant is composed of 120,120 polycrystalline PV panels (250 W each), 22 panels per chain. The PV panels are fixed at a 30° tilt angle and oriented to the south. The plant has 30 inverters (02 × 500 kW). The SKTM PV power plant is a part of the national renewable energy and energy efficiency program. The power plant is expected to produce 52,000 MWh of electricity annually and reduce CO_2 emissions by about 30,000 tons/year. **Figure 3-5** shows the SKTM power plant and its location.

Similar to most PV systems installed in arid areas, the SKTM power plant also faces harsh environmental conditions such as high temperatures and dust accumulation. In order to mitigate power losses due to dust accumulated on PV modules, a truck-mounted cleaning system was provided to the power plant to clean soiling and deposited dust on the surface of PV modules. This cleaning truck consisted of a water tank (5000 l), a water pump, and two rotating brushes attached to the truck alimented by water pressure. However, this technique was not an appropriate solution as it requires large quantities of water and water sources are scarce in the region. Consequently, the PV power plant was cleaned naturally by rain or manually using dry brushes.

Figure 3-5 Site of on-grid PV power plant (SKTM Ouargla) as seen in Google Earth.

4. RESULTS AND DISCUSSION

4.1. Effect of solar irradiation intensity

PV power outputs of the clean SYP80S-M monocrystalline photovoltaic module have been evaluated experimentally under outdoor climatic conditions with different levels of solar irradiation from 08:30 until 16:30 local time during a clear day (July 10, 2018) to determine the effect of irradiance intensity on performance of the PV modules. Solar irradiation, ambient temperature, and electrical characteristics of the PV module were recorded every 30 min. **Figure 3-6** shows the recorded solar irradiation and ambient temperature values for the test day.

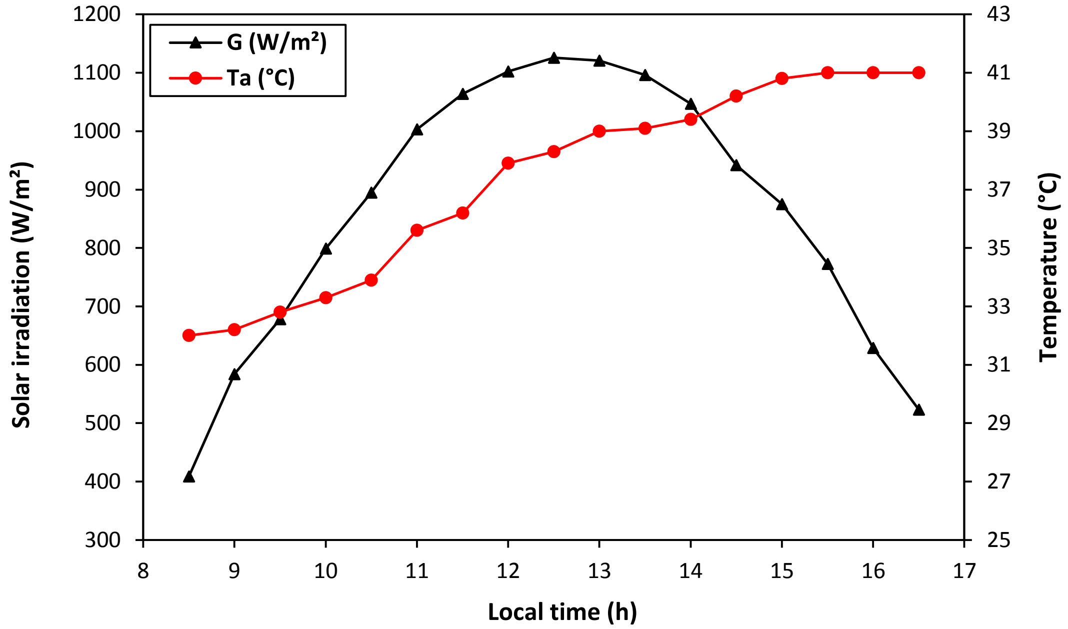


Figure 3-6 Solar irradiation and ambient temperature values (July 10, 2018).

Figure 3-7 and **Figure 3-8** show I-V and P-V characteristics of the SYP80S-M (80W) PV module, respectively, under outdoor conditions with different solar irradiation levels. The results showed that the highest power output and short circuit current values were recorded at the irradiation value of 1121 W/m^2, while the lowest power output and short circuit current values were observed at 584 W/m^2, indicating that the maximum output power and the short circuit current are directly proportional to the solar irradiation. This means that PV power output and short circuit current increase with an increase in solar irradiation. However, a slight decrease in maximum and open circuit voltage was noticed due to the increased temperature. These results demonstrate the importance of solar irradiation intensity on the performance of PV modules.

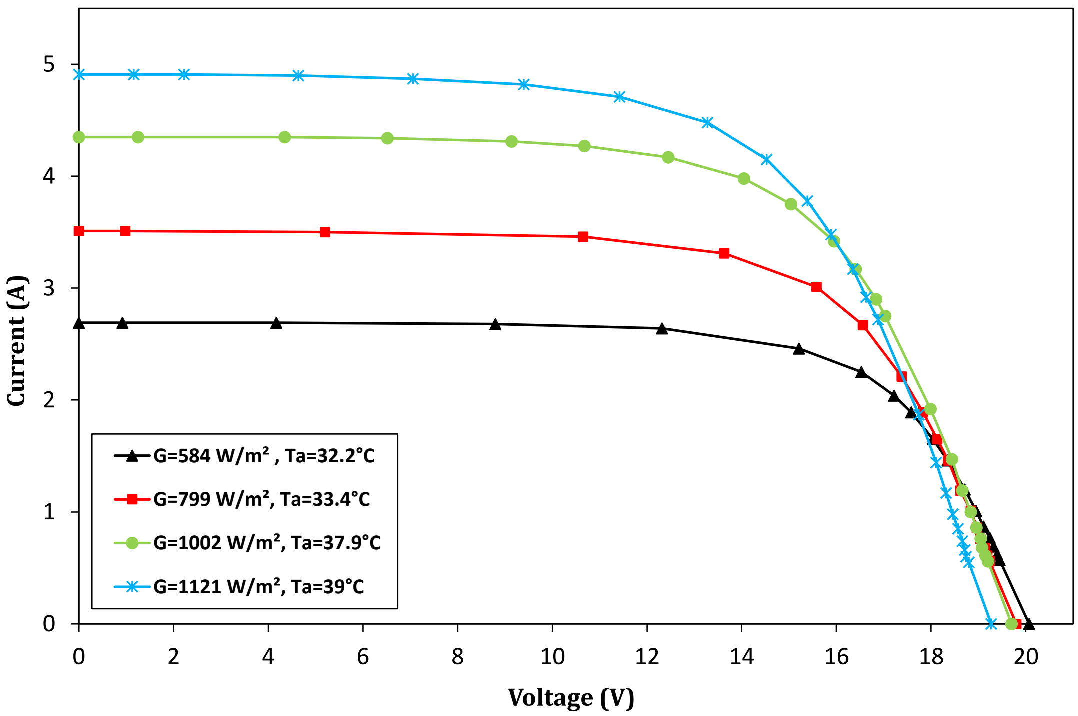


Figure 3-7 I–V curves of a clean PV module under external conditions.

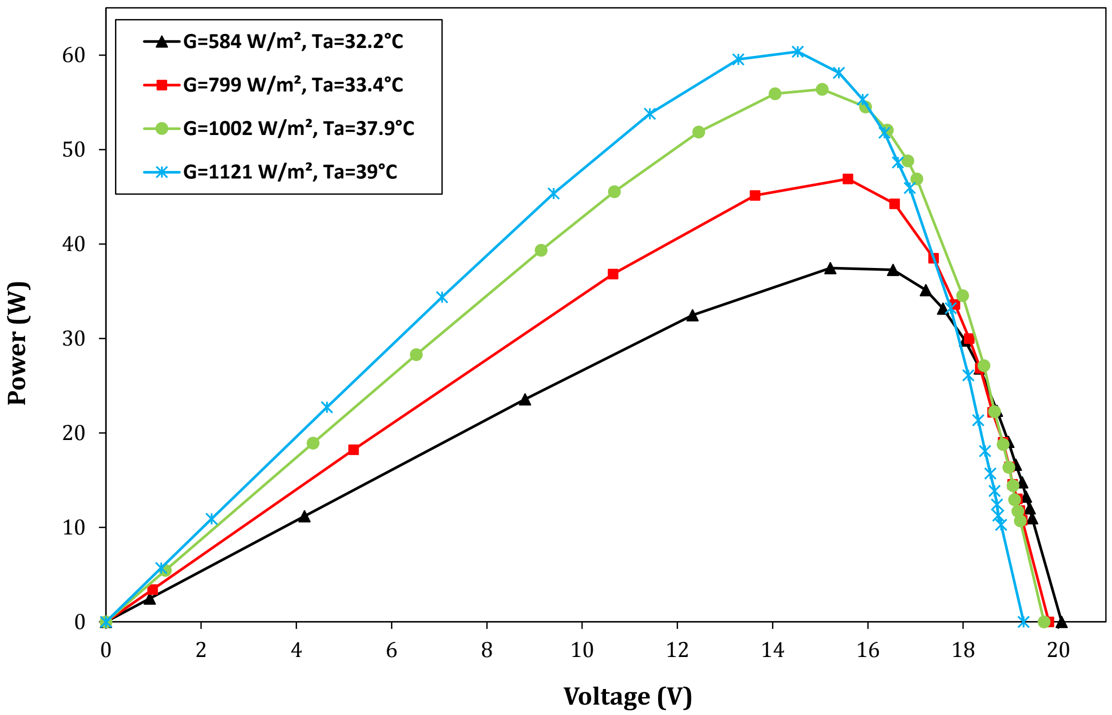


Figure 3-8 P–V curves of a clean PV module under external conditions.

4.2. Effect of dust accumulation

The laboratory tests that were carried out under outdoor conditions started on May 15, 2018 and terminated on July 10, 2018. The exposure duration was a dry period characterised by a total absence of rain (0 mm), no sandstorm occurrences, and an average wind speed of 4.76 m/s. The daily average irradiation and maximal and minimal temperatures during the test period are illustrated in **Figure 3-9** (ONM).

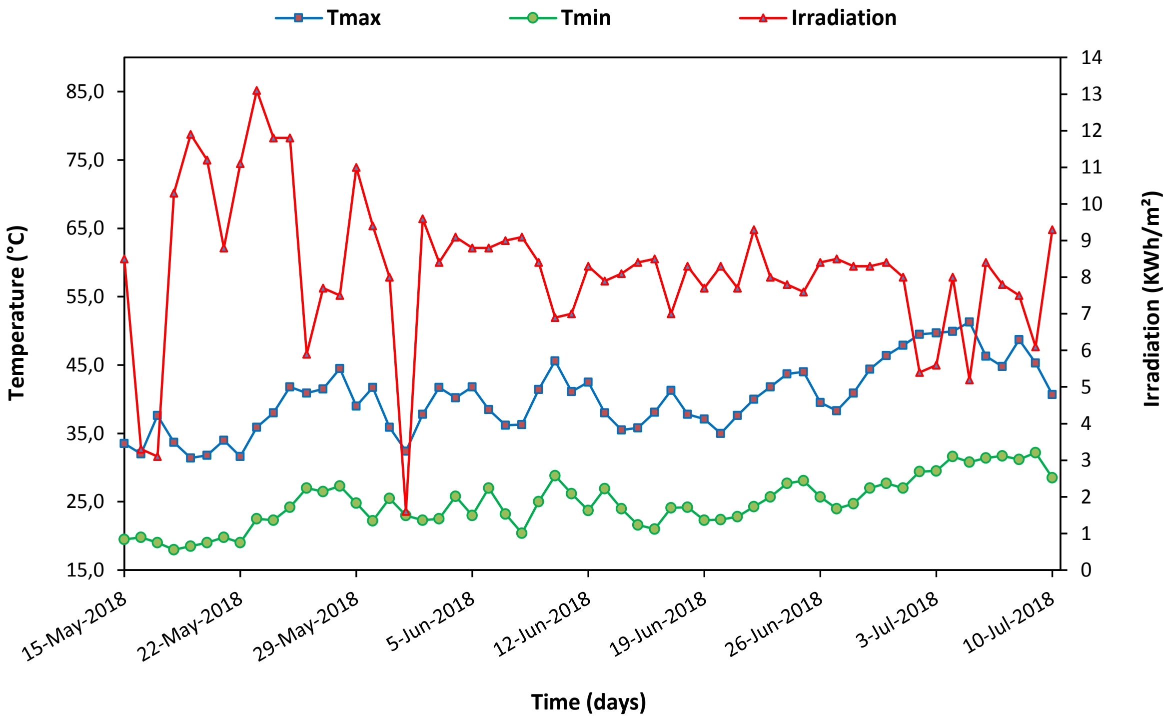


Figure 3-9 Daily average irradiation and ambient temperatures during the test period.

A dusty solar PV module was compared to a clean module. Both P-V and I-V curves were plotted using Microsoft Excel. The maximum power was obtained at a maximum voltage and a maximum current condition.

As illustrated in **Figure 3-10**, the PV output power and the short circuit current decreased due to the accumulation of 2.6962 g/m^2 of dust after two weeks of outdoor exposure by approximately 5.71% and 4.06%, respectively, compared to the clean module. It was also observed that the reduction in maximum power output and short circuit current increased with dust density. The short circuit current and maximum power reduction after eight weeks of outdoor exposure without cleaning, caused by the accumulation of 4.3619 g/m^2 of dust, were 6.10% and 8.41%, respectively. The reduction in the maximum power and the short circuit current increased with the increasing of outdoor exposure period. This was mainly due to the increase of the accumulated dust on the surface of the photovoltaic panel, which led to a reduction in the solar irradiation reaching the solar cells.

Figure 3-11 and **Figure 3-12** show the obtained I-V and P-V curves, respectively, of the PV module samples recorded under clean and dusty conditions. The results show lower values for both I-V and P-V curves of the dusty module because of the accumulation of 4.3619 g/m^2 of dust after eight weeks of exposure in external conditions without cleaning, compared to the clean module.

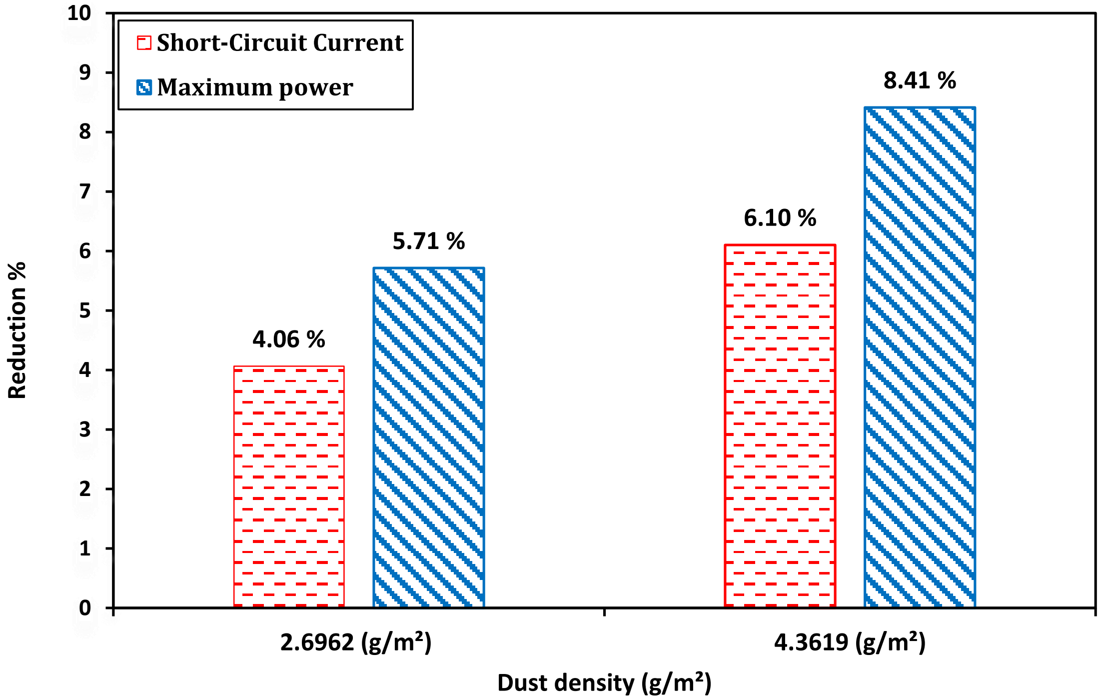


Figure 3-10 Maximum power output and short circuit current reduction due to dust accumulation versus dust density.

These curves indicate a performance degradation due to the decrease in solar irradiation received by solar PV cells because of dust deposition on the module's surface. The discrepancy between these curves was expected to augment with outdoor exposure time due to the increase of dust density on the module's surface. The effect of 4.3619 g/m^2 of deposited dust after eight weeks of outdoor exposure without cleaning on the characteristics of electrical parameters of the modules is shown in **Table 3-2**.

Short-circuit current and maximum power values were significantly affected by dust deposition on solar panels with a decrease of about 6.10% and 8.41%, respectively. In contrast, open-circuit voltage output was less sensitive to dust accumulation, and reduced by only 0.51% compared to values recorded in clean conditions.

Table 3-2 PV module parameters for clean and dusty modules (1121 W/m^2, 39 °C).

Parameter	**Clean module**	**Dusty module**	**Reduction %**
Maximum power (W)	60.38	55.3	8.41
Short-circuit current (A)	4.91	4.61	6.10
Open-circuit voltage (V)	19.27	19.17	0.51

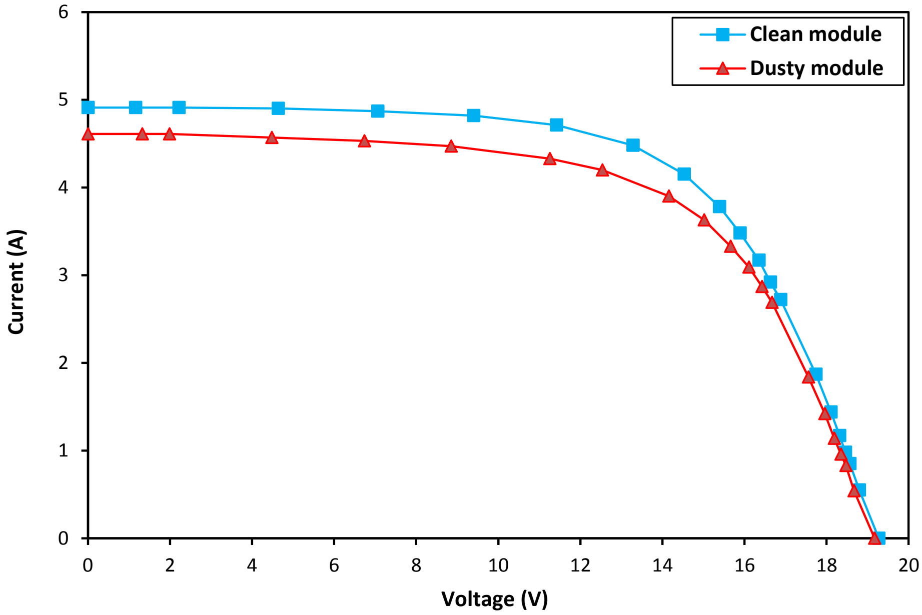


Figure 3-11 I–V curves of dusty and clean PV modules under external conditions (G=1121 W/m^2, Ta = 39 °C).

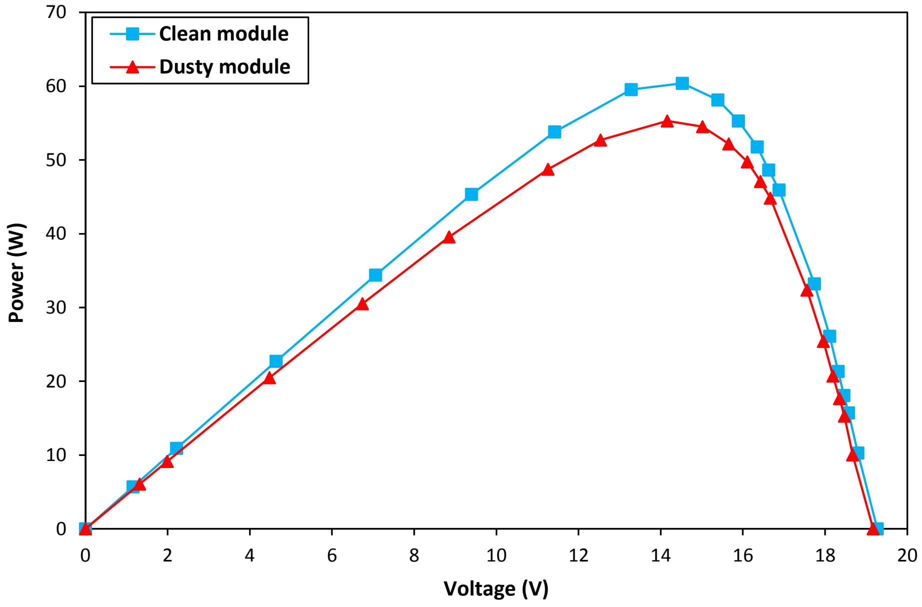


Figure 3-12 P–V curves of dusty and clean PV modules under external conditions (G=1121 W/m^2, Ta = 39 °C).

Figure 3-13 shows the variation of maximum power output for clean and dusty modules compared with the variation of solar irradiation intensity at different times of the day (July 10, 2018). Results illustrate that the maximum power output for both modules was directly proportional to solar irradiation values. Furthermore, the maximum power output for clean module was higher than that of the dusty module throughout the day for different levels of solar irradiation.

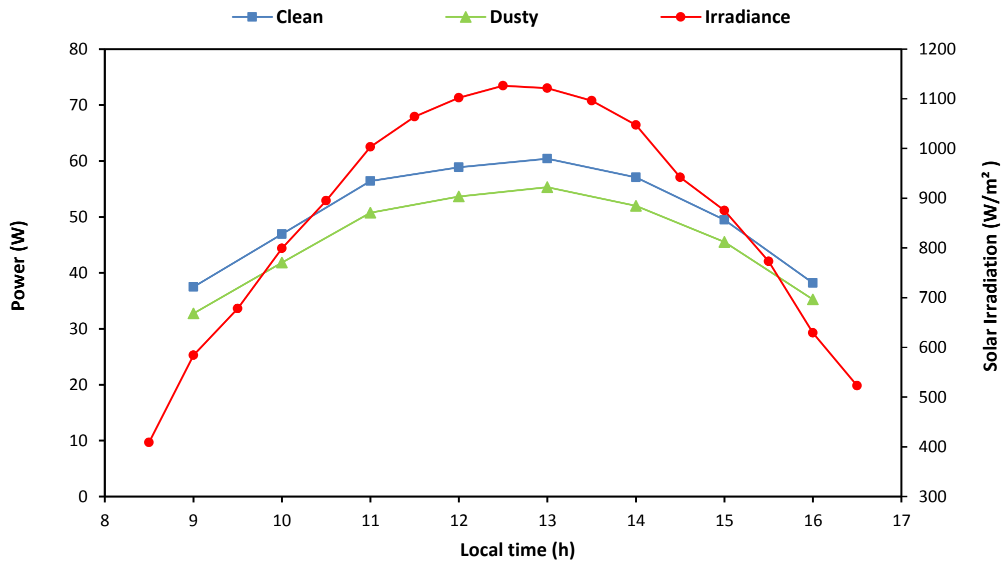


Figure 3-13 Variation of solar irradiation and maximum power output for clean and dusty modules with local time of day.

4.3. Dust proprieties

For a fuller understanding of the effect of dust deposition on the performance of PV systems, the accumulated dust on the glass surface of the PV panel was collected and analysed by using an XRF Spectrometer (S1 Titan, trademark: Bruker, USA).

It was found that the deposited dust consisted mainly of Si (52.16%), Fe (16.69%), Al (5.33%), In (4.34%), Ti (4.02%), Mg (3.56%), Rh (3.43%), Zr (3.43%), S (2.64%), Ru (2.23%), Pd (1.18%), Mn (0.26%), Ni (0.16%), Y (0.16%), Cr (0.13%), and Cu (0.09%).

Figure 3-14 shows the average ratios of accumulated dust components. These results are similar to the results from other studies (Gholami et al., 2018; Zeki Ahmed Darwish et al., 2015). The average ratios of dust compounds may differ from region to another due to the difference of geographical characteristics and environmental climatic conditions.

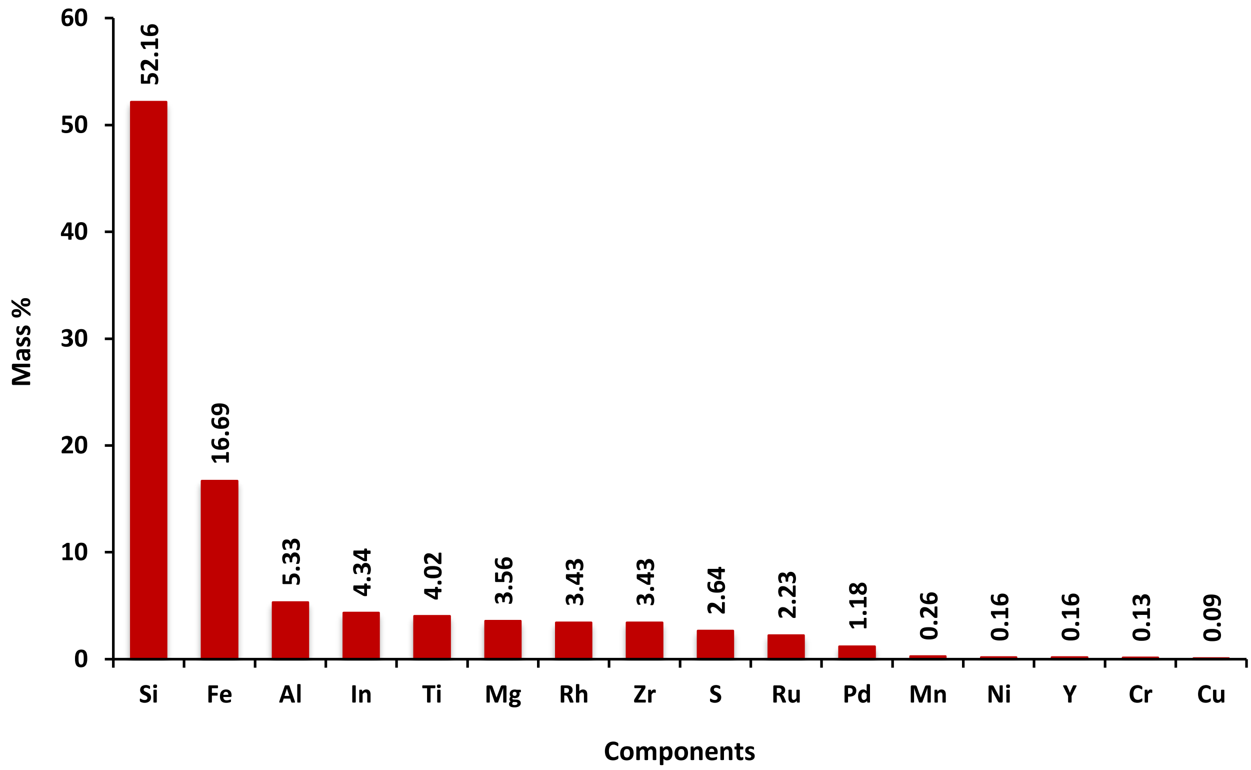


Figure 3-14 Average ratios of accumulated dust sample components.

4.4. Effect of sandstorms

Power generation measurements

The electrical characteristics of the PV power plant and weather conditions were recorded every 20 s using a NARI NC2000 computer monitoring system and a NARI weather station, respectively. The power production measurements of the 30 MW PV power plant (SKTM, Ouargla), Algeria were carried out on three different climatic conditions (before, during, and after a sandstorm day):

- Sunny day (before the sandstorm, 26 October 2018).
- Sandstorm day (28 October 2018).
- Sunny day (after the sandstorm, 30 October 2018).

The PV power plant was hit by a sandstorm during the day (28 October 2018), which was characterised by a large amount of dust and a small amount of non-continuous rain (0.62 mm), which led to an increase in the adherence of dust particles on the surface of the PV solar panels. **Figure 3-15** shows the accumulated dust on the modules of the on-grid PV power plant after the sandstorm day. During the sandstorm day, the average relative humidity was 41.3%. Solar irradiation and ambient temperature values during this day are illustrated in **Figure 3-16**.

Figure 3-17 shows solar irradiation values during the day (26 October 2018) before the sandstorm and the day (30 October 2018) after the sandstorm. Both curves were similar throughout the day with a little variation, which was noticed from 10:00 to 15:00. The day after the sandstorm recorded lower values than the day before the sandstorm with a maximum decrease of about 2.43% recorded at 12:40.

Figure 3-15 Photograph of accumulated dust on PV modules.

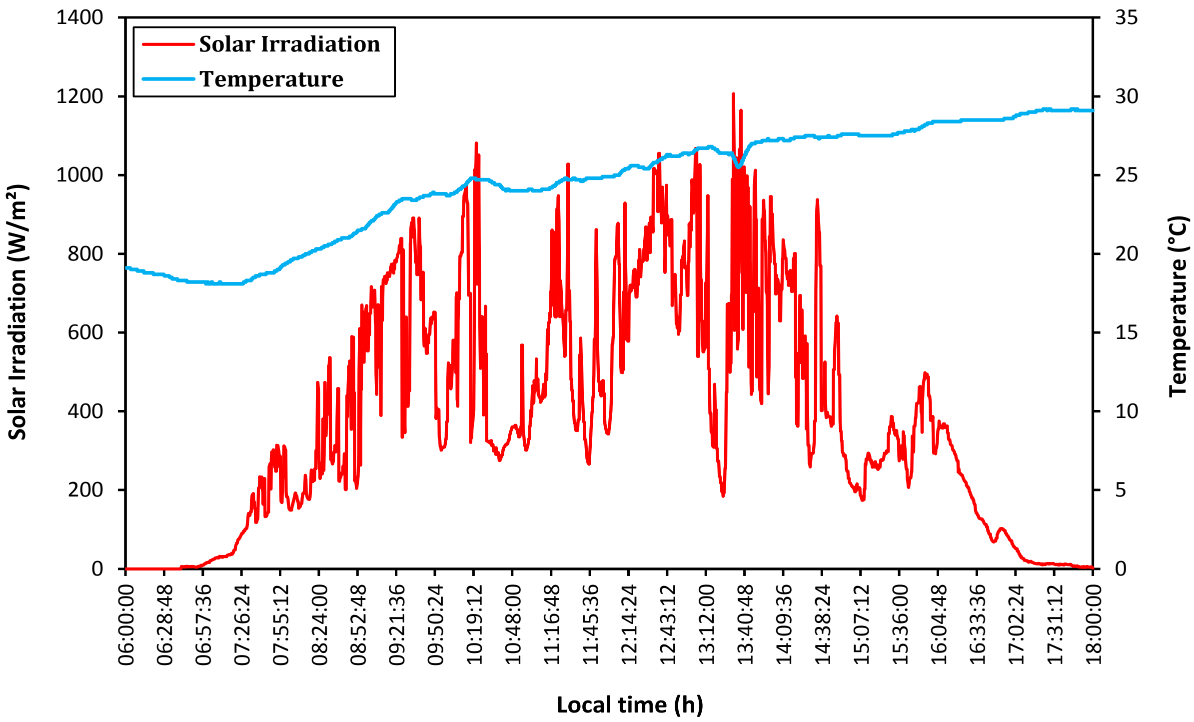


Figure 3-16 Solar irradiation and ambient temperature values during the sandstorm day.

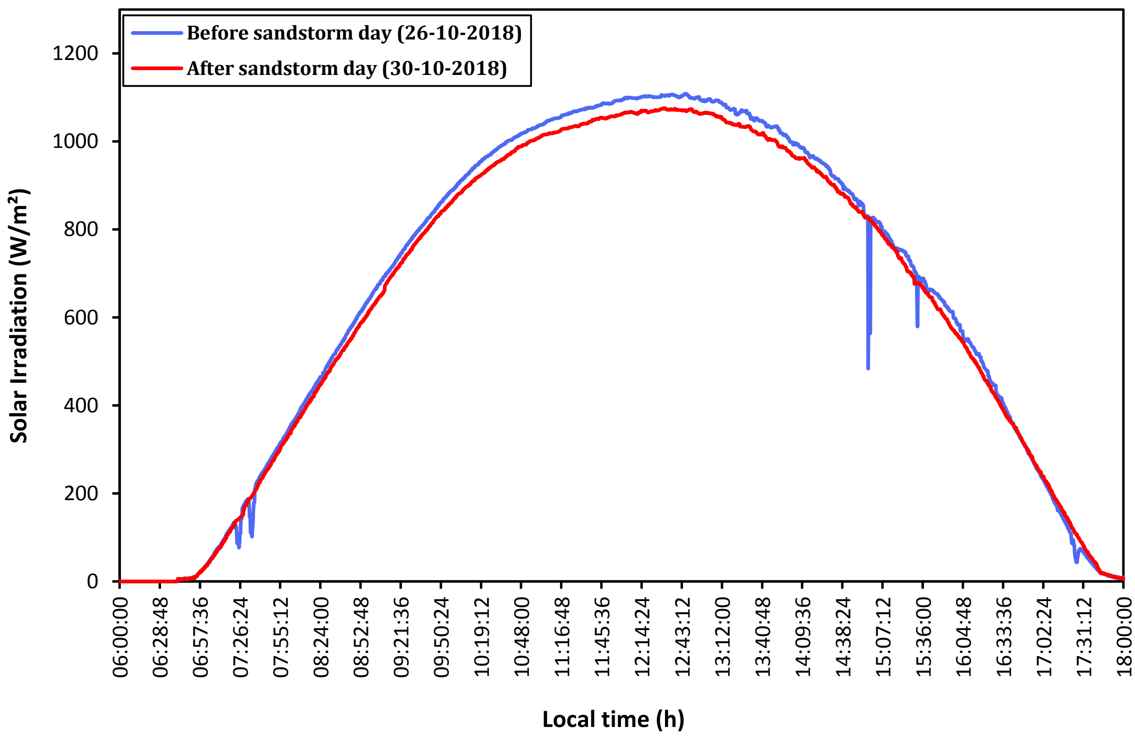


Figure 3-17 Solar irradiation values during the day before and the day after the sandstorm.

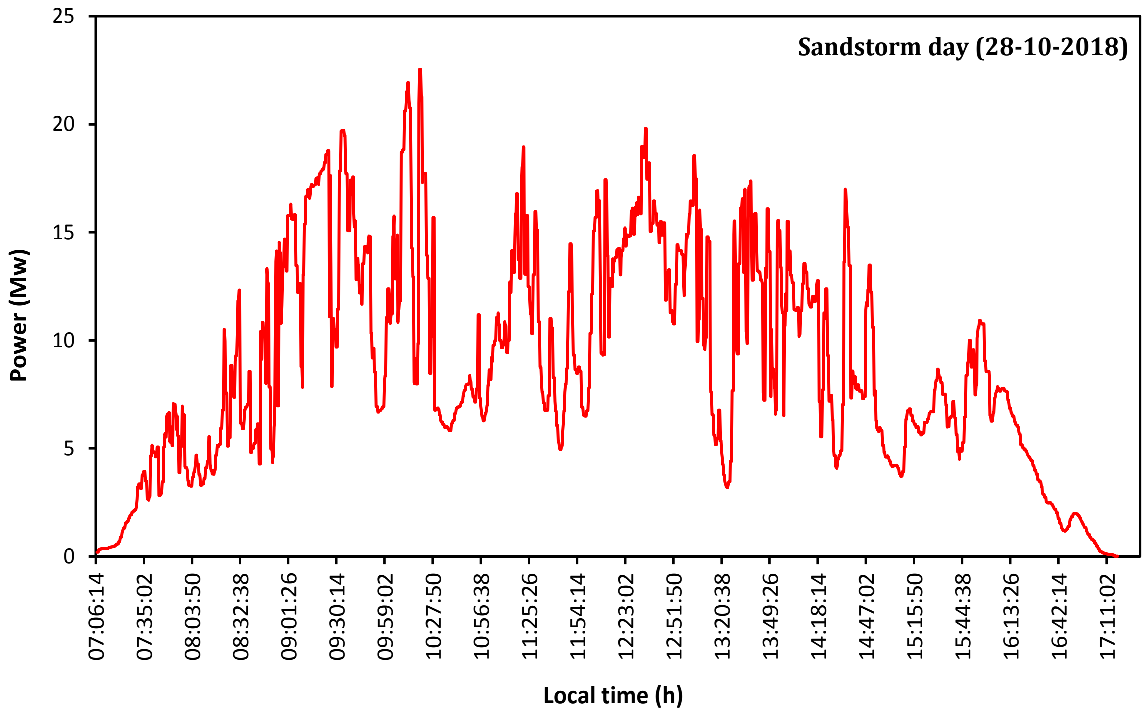


Figure 3-18 Power generation during sandstorm day.

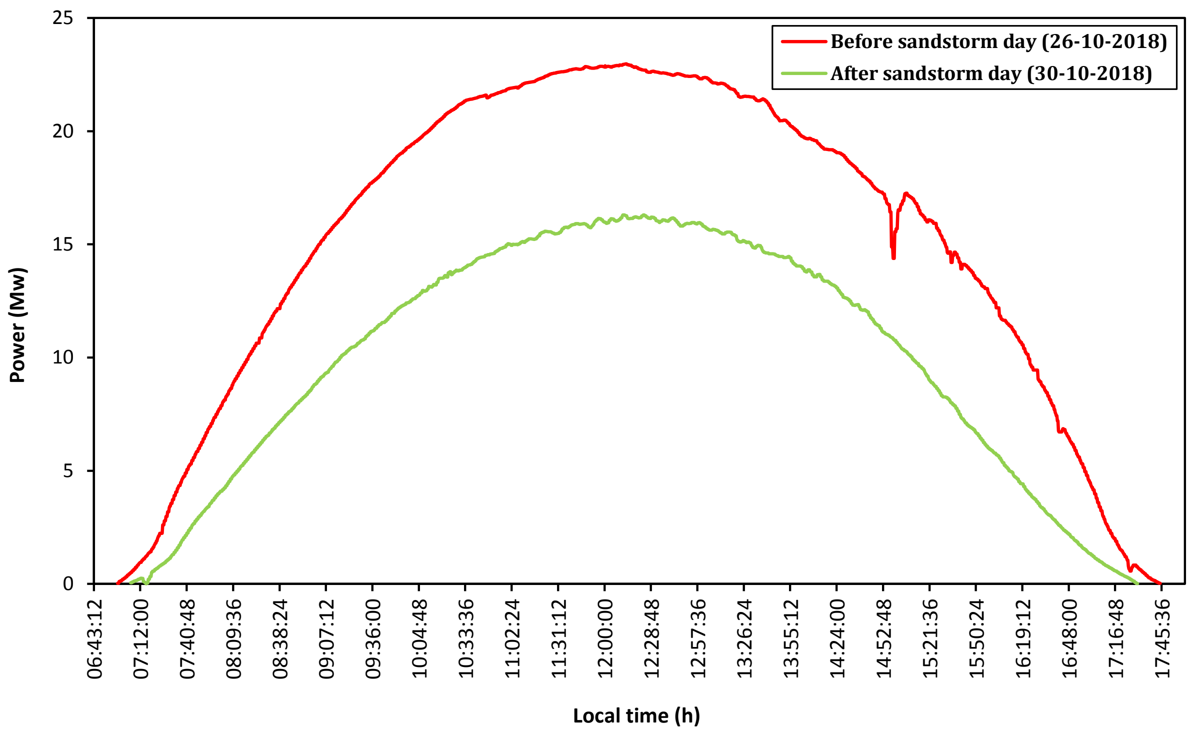


Figure 3-19 Power generation during clear days (before and after sandstorm).

Figure 3-18 shows the daily power generation of the grid-connected PV power plant during the sandstorm day (28 October 2018). The PV power plant energy production recorded lower values and an unstable performance with many peaks throughout the day. This was mainly due to the inappropriate climate conditions, especially the rapid variation in solar irradiation as a result of the sandstorm where the dust particles scattered in the ambient air prevented solar irradiation from reaching the PV cells, resulting in a significant drop in the performance of PV power conversion.

Figure 3-19 displays the daily power generation of the grid-connected PV power plant during the clear day (26 October 2018) before the sandstorm and the clear day (30 October 2018) after the sandstorm. It was observed that the average energy generation before the sandstorm day was 15.75 MW/h and after the sandstorm day was 10.57 MW/h, indicating a degradation in the PV system performance by more than 32.85% as a result of the sandstorm. Furthermore, the maximum power values were 22.97 MW at 12:14 and 16.32 MW at 12:11 for the days before and after the sandstorm, respectively.

This reduction in daily energy generation of the grid-connected PV power plant after the sandstorm day was mainly due to accumulation of large amount of dust on the glass surface of PV modules. This decreased the solar irradiation received by the solar cells, which then led to a reduction in power generation of PV power plant.

4.5. Effect of natural cleaning (Rainfall)

To study and evaluate the effect of natural cleaning (by rainfall) of PV modules in arid and Saharan environments, a long-term experiment for a whole year from June 21, 2019 to June 20, 2020 has been performed under the climate of Ouargla. The effect of dust deposition and natural cleaning by the rain on PV modules performance of each season has been evaluated apart. Two polycrystalline PV modules (80W) were used in this experiment; one module (clean) was used as a witness **Figure 3-20**. The accumulated dust density was measured each (30 days) using a glass sample (see section 3.3.2). The electrical characteristics of PV modules were measured and compared each measurement day (chosen clear days). Rain falling data during the experiment period was collected and plotted as seen in **Figure 3-21**. The (12 months) experiment period were divided into four seasons (3 months each) as follow:

- **Summer:** from June 21, 2019 until September 20, 2019.
- **Autumn:** from September 21, 2019 until December 20, 2019.
- **Winter:** from December 21, 2019 until March 20, 2020.
- **Spring:** from March 21, 2020 until June 20, 2020.

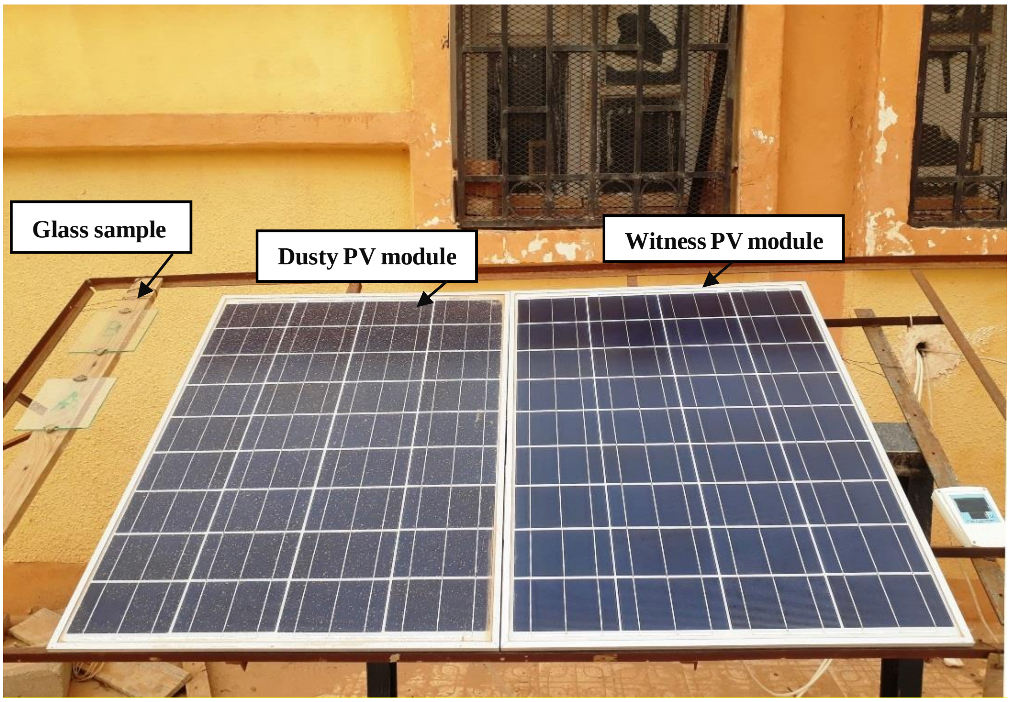


Figure 3-20 Experimental setup.

Figure 3-21 shows the rainfall data of Ouargla city recorded over a whole year involving all the four seasons. It is obvious that the highest rainfall rate was recorded during the spring period and in the last month of summer period. While, autumn and winter showed a very lack of rainfall, this explaining the accumulation of huge dust amounts on the PV module surface during these two periods leading to significant output power losses **Figure 3-22 (b, c)**. Since the power output reduction is directly related to the deposited dust density on the PV module surface, the power losses increase with the increment of accumulated dust density.

The output power reduction was 19% and 13.5% at the exposure period end of autumn and winter, respectively, **Figure 3-22 (b, c).** In contrast, summer and spring exposure periods showed less accumulated dust density and the output power reduction was only 3.8% and 1.2%

at the end of summer and spring seasons, respectively, **Figure 3-22 (a, d).** This mainly due to the automatic cleaning effect of the dusty PV module by rainfall. In the summer exposure period, the power losses reached to 9% on 21st of August. However, this value was dropped to 3.8% at the end of the season as a result of rain falling (5.3 mm), leading to natural cleaning of the dusty PV module and thus increased the output power.

Natural cleaning of PV modules by rainfall can contribute strongly on the mitigation of performance degradation caused by dust deposition. However, the cleaning effectiveness is directly dependent to the rain falling amounts. The recorded precipitation data in this study showed the scarcity of rainfall in the experiment region (Ouargla, South of Algeria), where rainfall occurs only in few days over a whole year. Therefore, it can be said that natural cleaning by rain falling is only effective in areas with high precipitations rate.

A performance comparison of this study with similar studies in different regions on the effect of dust deposition is summarised in **Table 3-3.**

Table 3-4 Comparison of this study with similar studies in other regions.

Reference	Region	PV Technology	Exposure Time	Dust density (g/m^2)	Output Power Reduction %
Present study	Ouargla, Algeria	Monocrystalline Polycrystalline Polycrystalline	8 weeks Winter (90 days) Sandstorm	4.3619 5.88 -	8.41 18.94 32.85
Adinoyi et al (Adinoyi and Said, 2013)	Dhahran, Saudi Arabia	Mono/Polycrystalline	Exceeds 6 months. Sandstorms	6.184 -	50 20
Gholami et al (Gholami et al., 2018)	Tehran, Iran	Monocrystalline	70 days	6.0986	21.47
Saidan et al (Saidan et al., 2016)	Baghdad, Iraq	Monocrystalline	1 month	0.64	15.87
Elminir et al (Elminir et al., 2006)	Cyprus	Monocrystalline	7 months	12	17.4 per month
Hachicha et al (Hachicha et al., 2019)	UAE	Polycrystalline	5 months	5.44	12.7

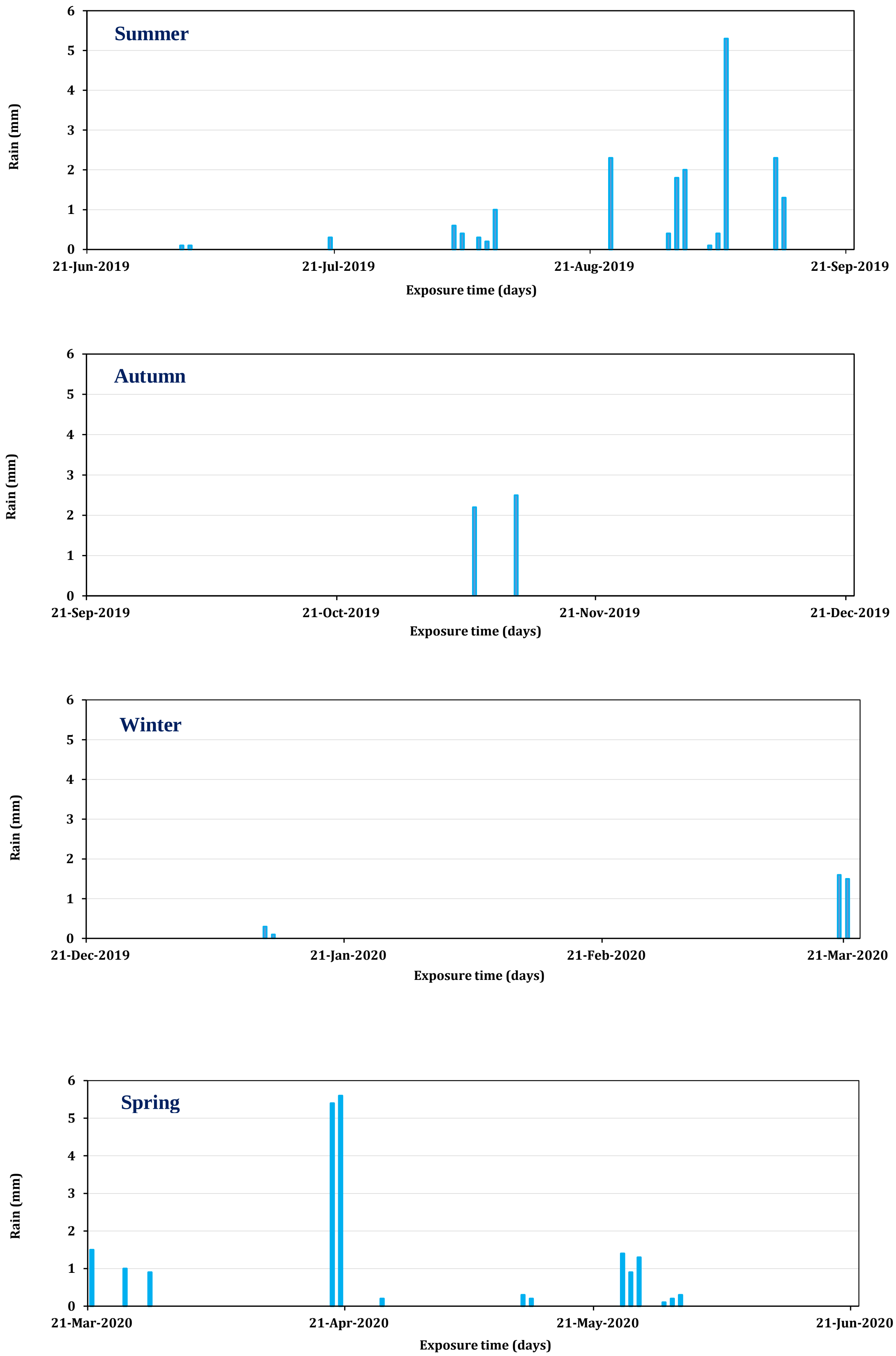
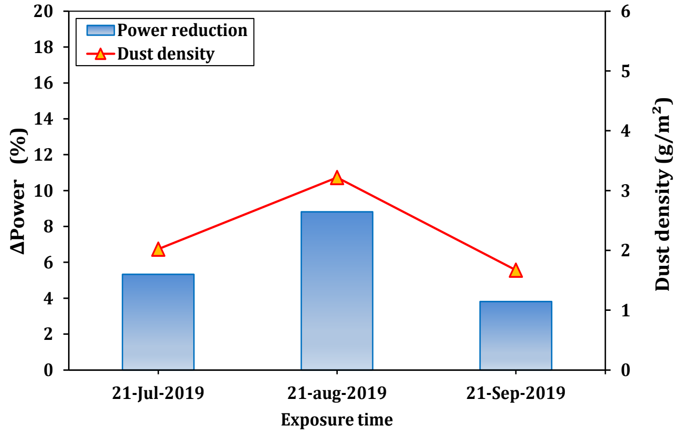
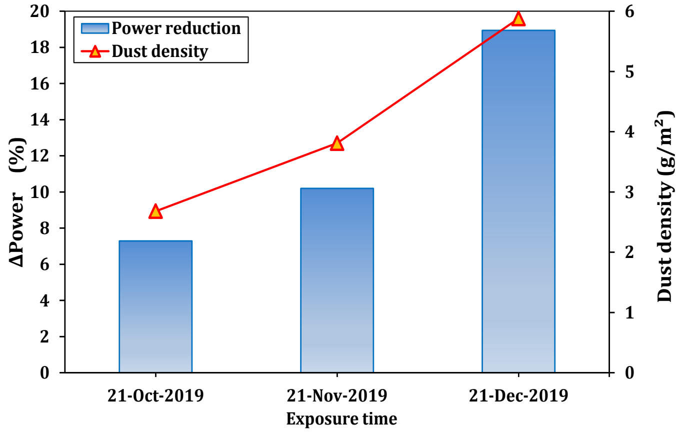


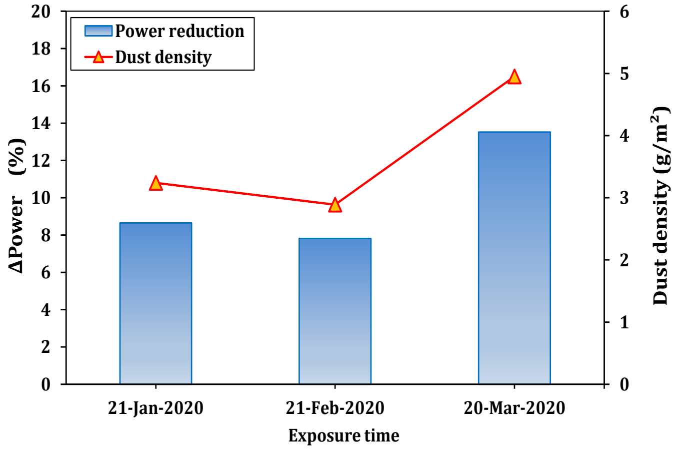
Figure 3-21 Rain precipitations for each season (ONM).



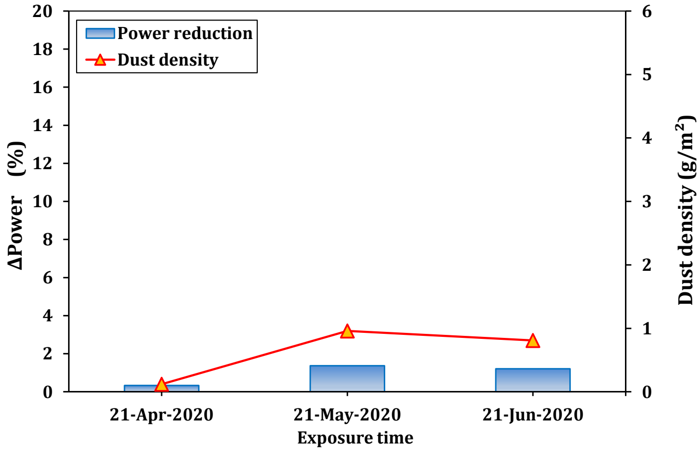
(a) Summer period



(b) Autumn period



(c) Winter period



(d) Spring period

Figure 3-22 Evolution of accumulated dust density and output power reduction for each season.

5. CONCLUSIONS

In the present chapter, an experimental investigation on the influence of solar irradiation, dust deposition, and sandstorms were carried out under the environmental conditions of a Saharan region (Ouargla, South of Algeria). The characteristics analysis of the deposited dust was also conducted. It was well observed from the results that the PV conversion efficiency is directly dependent to sunlight intensity. Dust accumulation on the glass surface of the modules has a major impact on the reduction of solar irradiation reached to the PV cells leading to a considerable output power loss. This output power loss increases with deposited dust density increment. The dust accumulation density increases with exposure time in dry periods. However, it is strongly related to the weather conditions such as dust event and rain falling during the exposure period. Results also showed that one sandstorm day was responsible for the accumulation of big dust amounts, which led to significant power losses of the PV power plant. Rain falling can provide a free cleaning of PV modules. Results showed that seasons with high rainfall rate had the least power loss due to the dust accumulation. However, natural cleaning by rain falling is not effective in arid and desert areas where the rain precipitations are scarce.

CHAPTER 4 EXPERIMENTAL STUDY OF A PASSIVE COOLING SYSTEM FOR PHOTOVOLTAIC CONVERSION IMPROVEMENT

1. INRODUCTION

Photovoltaic systems convert only a small amount of incident solar insolation into electrical energy while the rest is converted into heat. The increase in the PV cell temperature decreases significantly the electrical efficiency by about 0.5% for each 1 °C rise. Hence, it is necessary to keep the PV module temperature at low values to improve the efficiency and minimise the thermal degradation effect. The main objective of this chapter is to develop a passive cooling system based on water evaporation and the capillary action of burlap to fix the photovoltaic modules overheating problem in order to improve their conversion efficiency by reducing the operating temperature and maintaining a uniform temperature distribution over the module. The proposed water evaporation cooling system was investigated experimentally under real outdoor conditions during summer days in a hot region (Ouargla, South of Algeria). Thermal and electrical characteristics of used PV modules (with and without cooling) were analysed and compared. Furthermore, the investment cost and water consumption quantity were taken into account in order to improve the feasibility terms.

2. METHODOLOGY

2.1. Locale of experiments

The experiments were carried out during the summer of 2019 in clear hot days (August 17, 18 and 19) from 8:30 to 17:30 local time under outdoor environmental conditions of Ouargla city, Algeria. Ouargla is identified by high solar irradiation intensity, large number of clear sunny days and long duration of daily sunshine, which made it an appropriate area for PV power generation (Dida et al., 2020). However, it also has one of the highest ambient temperatures (often more than 45°C in summer) **Figure 4-1,** which is well known as a significant challenge for PV systems performance. On July 5, 2018, Ouargla recorded one of the hottest temperatures worldwide and the hottest temperature ever reliably measured in Africa, which reached 51.3 °C (wunderground). Moreover, it is characterised by low rainfall, the humidity rate is relatively low and the annual wind speed average is 3.70 m/s (ONM).

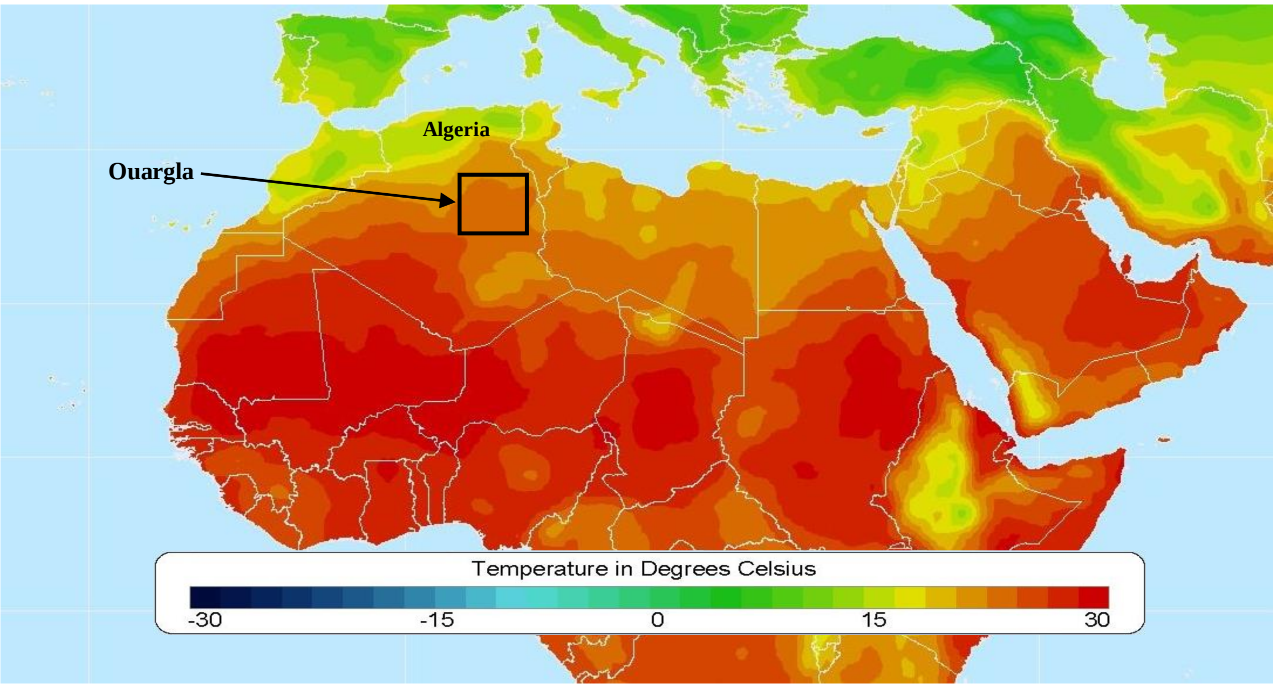


Figure 4-1 Average annual temperature of North Africa, Algeria and Ouargla (Atlas maps).

2.2. Preparation of the cooling system

Evaporative cooling is an old and effective cooling method; it was used for centuries to cool water and keeping fruits and vegetables fresh, especially in remote and dry agglomerations with hot climate and lack of electricity.

In this study, a passive cooling system has been developed to reduce the module's temperature in order to improve its efficiency. The proposed system is based on water evaporation and the capillary action of a burlap cloth attached directly to the back surface of the module. Burlap is a very strong, coarse cloth, made from vegetable fiber; it is a sustainable and environmentally friendly product and it is usually used to make gunny sacks, which is used for the transportation of agricultural products and foodstuffs such as cotton, vegetables, coffee and grains. **Figure 4-2** displays a sample of the used burlap cloth in this study.

Figure 4-2 Sample of the used burlap cloth.

2.3. Early tests

It should be mentioned that one of the most encountered difficulties during the realisation of the passive evaporative cooling system prototype was the fixing of the wetted burlap cloth on the back surface of the PV module.

The use of a heat resistant glue to fix the burlap cloth on the backside of the module made the burlap dry and that prevented its capillary action resulting in a partially wetted burlap cloth, which creates hotspot points due to the no uniform cooling of the module.

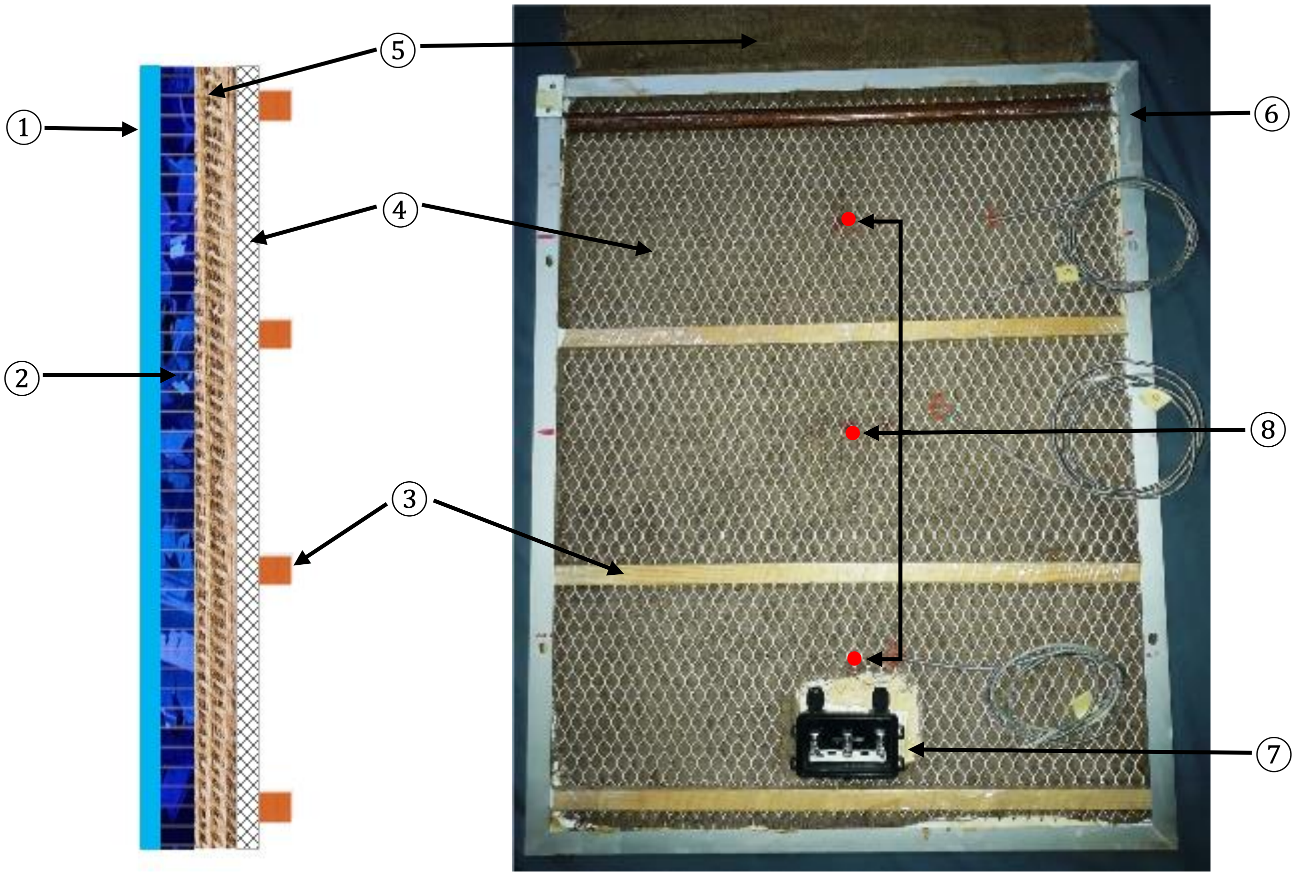
Using many bars to assert the contact between the burlap and the backside of the module, proved ineffective. This mainly was due to the need of using a large number of bars and that covered a considerable surface of the burlap cloth; this reduced the contact surface between the wetted burlap cloth and the surrounding air, resulting in the crippling of the evaporative cooling process.

Moreover, another problem was how to assert the continuous water feeding of the burlap cloth without the support of an additional power source. The use of a pipe with many small holes on the top of the module's back results in a slow and uneven distribution of water and thus low and non-uniform cooling. The utilisation of many pipes with several small holes leads to the consumption of huge quantities of water, which requires a big water tank or an external power source.

2.4. Final prototype

After many attempts and tests, the final prototype of the passive cooling system that ensures a permanent contact of the wetted burlap cloth with the backside of the PV module, low water consumption and a uniform cooling of all parts of the photovoltaic panel was realised.

To perform the proposed passive cooling system based on the capillary action; a burlap cloth (1.5 mm of thickness) was attached directly to the backside of the module. A light steel grid (1 mm of thickness) was placed on the Burlap cloth; wooden rods with appropriate sizes were placed between the steel grid and the aluminum frame of the module. The steel grid and wooden rods were employed to assert the permanent adhesion and to enhance the contact between the burlap and the rear surface of the module when the burlap cloth is wet. The wooden bars push the steel grid, which in turn fixes the burlap cloth to the backside of the module. A water resistor paint was used to protect the steel grid and the wooden rods from corrosion and decay respectively, due to water contact. The cross sectional schema and the back view of the PV module with the cooling system are shown in **Figure 4-3.**



1) Glass cover. 2) PV cells. 3) Wooden rods. 4) Steel grid. 5) Burlap.
6) Aluminum frame. 7) Junction box. 8) Thermocouples location.

Figure 4-3 The cross sectional schema and the back view of the PV module with the proposed passive cooling system.

2.5. Experimental process

Inarguably, water is the core of the passive evaporative cooling system in this study. The water supply quantity and quality affect directly on the heat transfer and the evaporative cooling effect. In the present study, the feeding water was merely asserted by the capillary action of the burlap cloth with the help of gravity force without the need of any external power source.

Capillary progression can be described as the macroscopic flow of water under the effect of its own interface forces. Before the water being transported, it makes the fibrous material wet. Since the capillary forces are caused by wetting, capillarity is a result of spontaneous wetting in a capillary system (Das et al., 2007). The interaction between the cohesive forces within the water and the adhesion forces between the water and the fibres play a key role in spreading and absorption of water over the textile material's surface. The process of water transport through fabrics and texture materials is illustrated in **Figure 4-4** (Azeem et al., 2017).

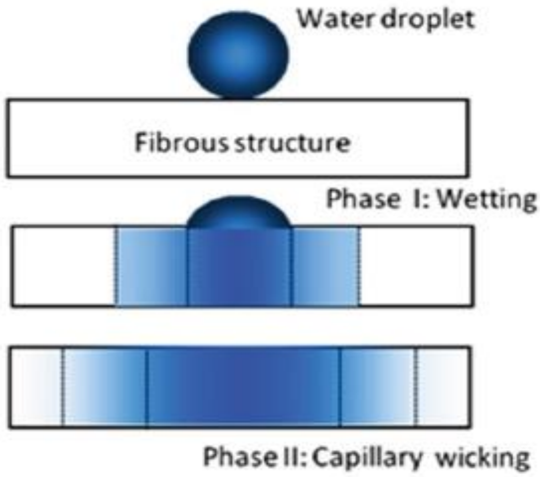


Figure 4-4 Water transport process through fabrics.

A 50-litre water tank was utilised as the main source of water, which feeds through a manual valve the water supply basin where the upper part of the burlap is immersed. Water is transferred by capillarity from the basin to all parts of the burlap cloth on the backside of the photovoltaic panel. An elastic pipe and a (5 L) water tank were used to regain the collected water through a small hole in the bottom of the aluminium frame of the module. The main advantage of this cooling system is that it can assert the wetting continuity of the burlap cloth to meet the requirements of evaporation cooling throughout the day without any water wasting. The experimental process of the proposed cooling system is displayed in **Figure 4-5.** The two main emphasised parameters in the present study are the continuity wettest of the burlap cloth with lower water consumption.

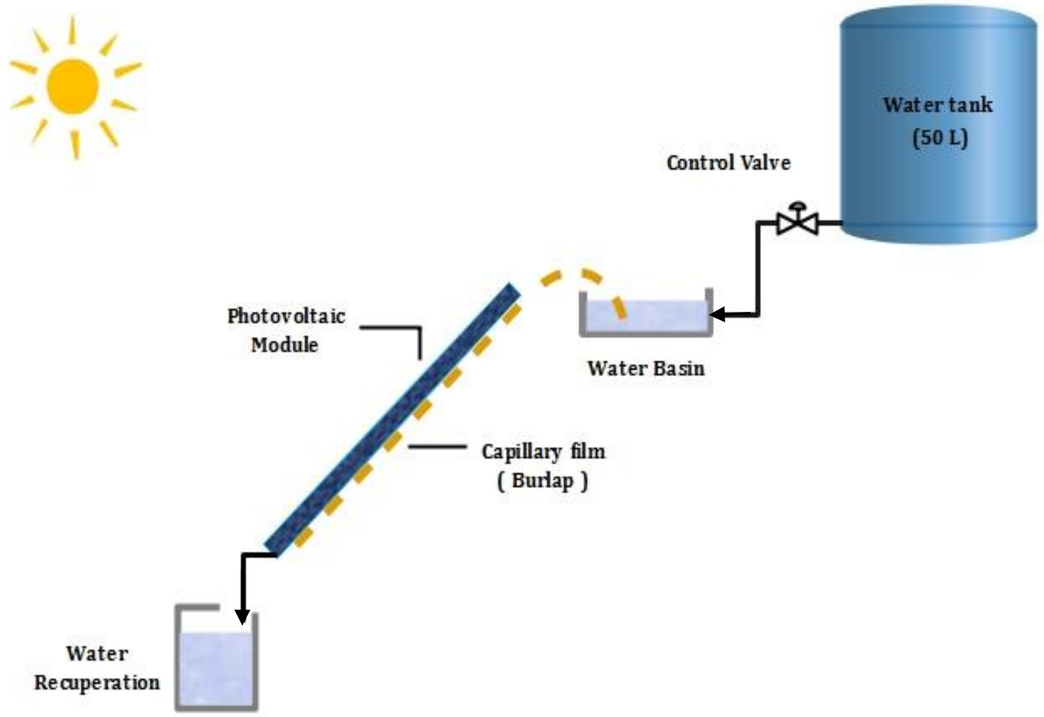


Figure 4-5 Schematic diagram of experimental process of the cooling system.

2.6. Measurement system

Two identical polycrystalline silicon PV modules with a maximum output power of 80W were used in this study. One module with the proposed passive cooling system, while the other was taken as a reference **Figure 4-6**. The modules were installed on the rooftop of a building near the university of Ouargla. Both modules were faced to the south with a fixed inclination of the latitude for Ouargla city location (31° 57’). The experiments were conducted in August 17, 18 and 19, 2019 from 8:30 to 17:30 local time. **Table 4-1** presents the electrical specifications of the used polycrystalline PV module under standard test conditions (STC).

The electrical characteristics of both the reference and the test (cooled) modules were monitored and measured using a variable resistor (PHYWE SE6) considered as a load resistor and digital multi-meters (METEX ME-31) to measure the module output power in terms of current and voltage. Three K-type thermocouples were placed vertically in different positions on the back surface of each module to measure the operating temperature **Figure 4-3.** These thermocouples were connected to a (Keithley 2750) data logger, which transferred data measurements to a computer. Weather parameters of the test days such as ambient temperature, solar irradiation and wind velocity were monitored and measured using a K-type thermocouple placed in a special container, LP02 pyranometer and a (Testo 425) hot wire anemometer, respectively. Specifications details of the utilised measurement instruments according to the technical data sheet of instrument producers are given in **Table 4-2**.

Table 4-1 Technical specifications of the used polycrystalline photovoltaic modules under STC (Ta = 25°C, G = 1000 W/m^2).

Parameter	**Specification**
Technology	Polycrystalline
Maximum power (W)	80
Maximum voltage (V)	17.4
Maximum current (A)	4.61
Open circuit voltage (V)	22
Short circuit current (A)	4.85
Number of cells	36 (4×9)
Area (mm^2)	900 × 670
Weight (kg)	6.9

Table 4-2 Technical specifications of measurement equipements.

Parameter	**Instrument Model**	**Range**	**Accuracy**
Solar irradiation	LP02 Pyranometer	0 – 2000 W/m^2	± 1.8 %
Temperatures	K-type thermocouples	-200 – 1260 °C	± 2 %
Wind velocity	Testo 425	0 – 20 m/s	± (0.03 m/s)
DC - Current	METEX ME-31	0.002 – 20 A	± (0.3 – 0.8 %)
DC - Voltage	METEX ME-31	0.2 – 200 V	± 0.05 %
Load resistor	PHYWE SE6	0 – 33 Ω	± 10 %

Figure 4-6 Front view of the experimental test setup.

3. RESULTS AND DISCUSSIONS

The experimental tests were carried out under real outdoor conditions of Ouargla city over a period of three clear days; August 17, 18 and 19, 2019, from 8:30 until 17:30 local time. The progression of solar irradiation and ambient temperature throughout the test days are displayed in **Figure 4-7** and **Figure 4-8**, respectively. As could be readily observed from **Figure 4-7**, the three test days were completely clear and had practically the same curve behaviour of solar intensity throughout the day, with highest recorded values of about 800 W/m^2 at 13:30. However, there was a little difference in the ambient temperature, as shown in **Figure 4-8,** the maximum temperature reached 40.6°C, 41.5°C and 43.7°C on the 17th, 18th and 19th of August 2019, respectively.

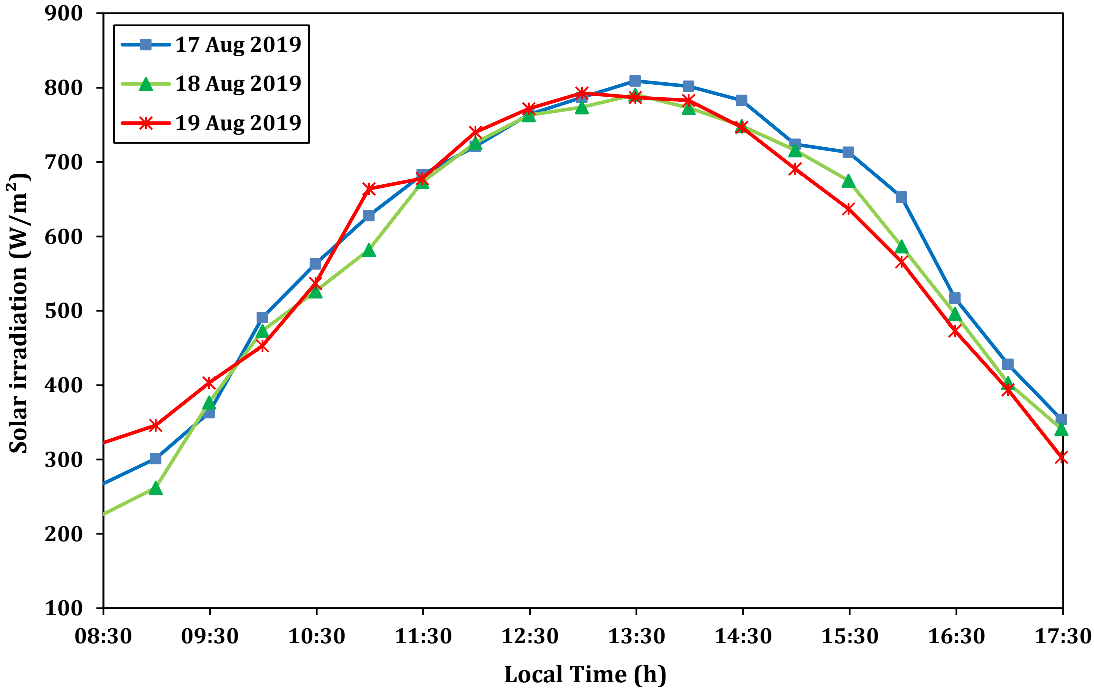


Figure 4-7 Variation of solar irradiation during the three test days versus local time.

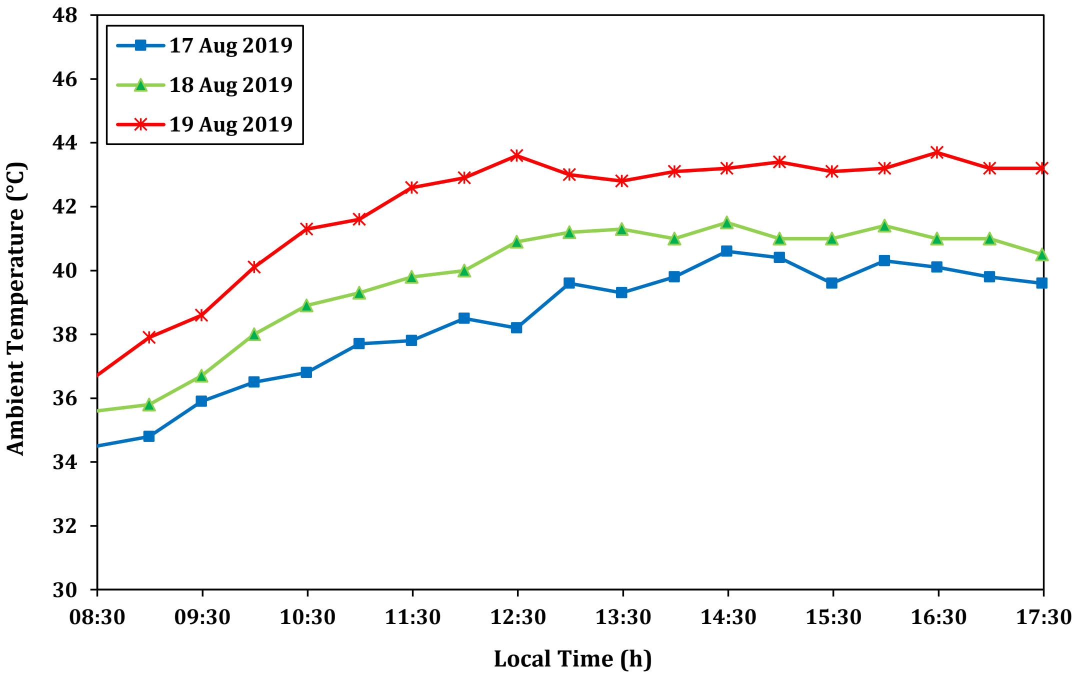


Figure 4-8 Variation of ambient temperature during the three test days versus local time.

3.1. Cooling effect on thermal characteristics

To study the effect of the developed cooling system on the thermal characteristics of the PV module, three K-type thermocouples were installed in different locations on the back surface of each module (cooled and reference modules). The recorded temperatures of the two tested modules at an interval of 1 min from 8:30 to 17:30 over the day (August 19, 2019) is plotted in **Figure 4-9**. The red (Tc1), green (Tc2) and black (Tc3) curves represent the temperatures of the cooled module. Whereas the purple (Tr1), orange (Tr2) and blue (Tr3) curves represent the temperatures of the reference module (without cooling).

By comparing the recorded temperatures, it could be observed that the backside temperatures of both modules were practically similar at the start of the experiment. However, when the cooling system was turned on, water transferred gradually by capillarity from the submerged part of the burlap to the entire surface of the burlap cloth attached to the rear surface of the module. When the burlap gets wet, the module temperature commences to decrease due to the process of water evaporation, which allows the heat absorption from the PV module.

As mentioned earlier, the three thermocouples were installed in three different locations (upper, middle and lower part) on the backside of the cooled module, which are represented by (red, green and black curves), respectively. At the commencement of the experimental measurements, both modules recorded identical temperature values. However, after few minutes, the temperature of the upper part of the cooled module started decreasing followed by that of the middle and lower parts. As could be noticed from **Figure 4-9,** it took about one hour (from 8:30 until 9:30) for the module to reach a lower uniform temperature. This is mainly due to the burlap wetting process, where water transferred gradually by capillarity from the upper to the lower part of the module.

It is apparent from the figure that after the full wetting of the burlap cloth, the module with cooling system has the lowest operating temperature compared to the reference one. Temperature curves illustrate also the uniform temperature distribution of the cooled module. The maximal recorded temperature of the witness module was 76.4 °C at 14:02 this was reduced to 55.8 °C due to the using of the cooling system. The average temperature of the reference PV module over the whole day was 66.4 °C, whereas the average temperature of the cooled one was only 49.3 °C, which represents about 26% reduction in the operating temperature due to the use of the developed evaporative cooling system.

Moreover, from **Figure 4-9, Figure 4-10** and **Figure 4-11** representing the measured temperature variations of both modules throughout the three test days; it is apparent that the used evaporative cooling system provided a uniform temperature distribution over the module surface throughout the day even at noon hours.

Low operating temperature and uniform distribution of temperature over the module surface contribute strongly in the protection of PV modules from thermal degradation and enhance their reliability. This makes the developed cooling system in this study as an attractive and effective solution for the performance improvement and thermal regulation of the modules especially in hot and arid areas.

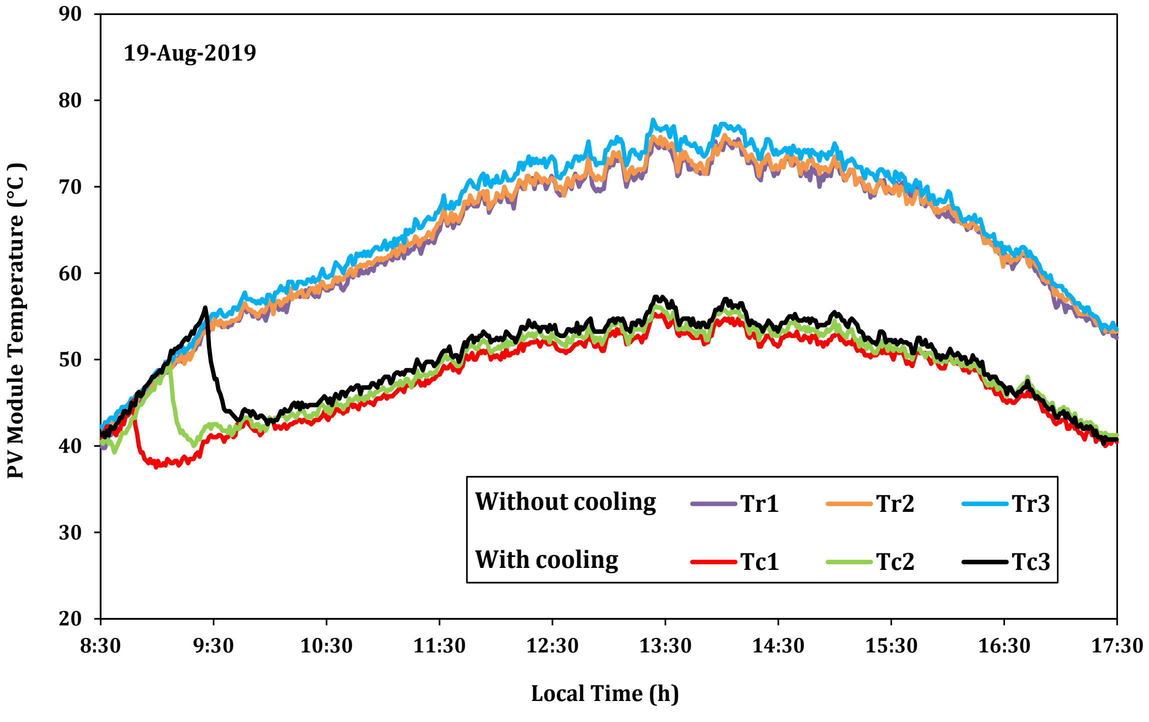


Figure 4-9 Temperatures of the cooled and reference PV modules (August 19, 2019).

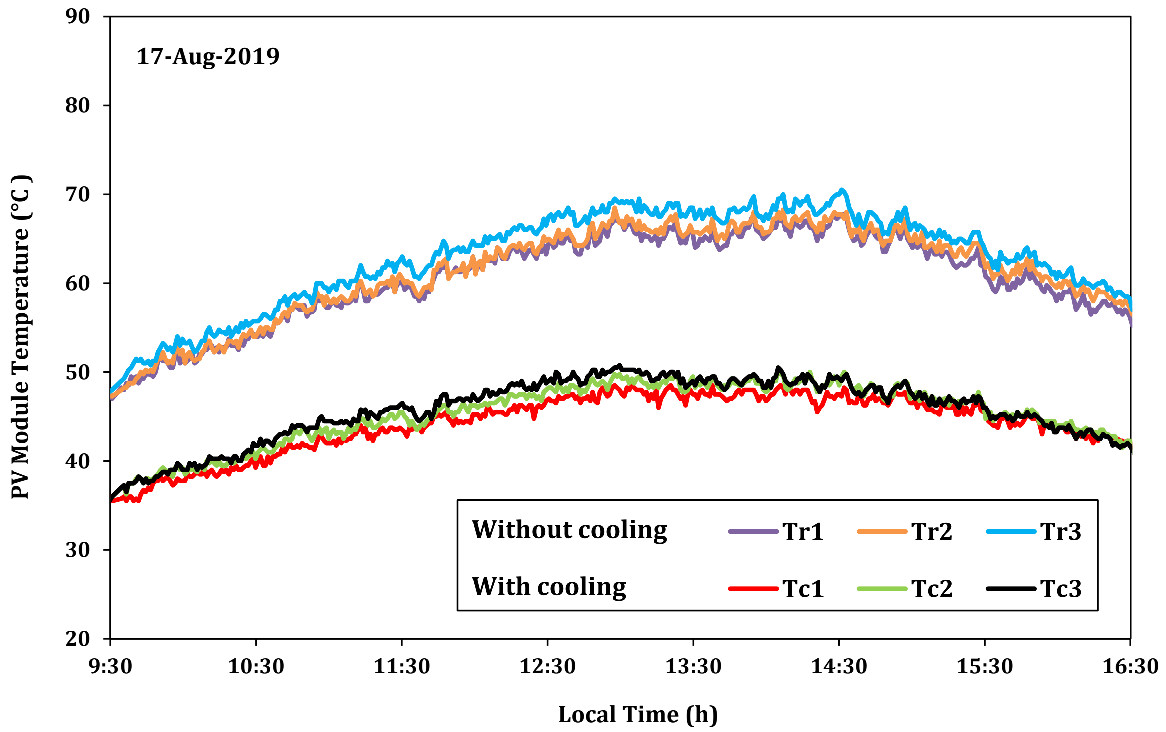


Figure 4-10 Temperatures of the cooled and reference PV modules (August 17, 2019).

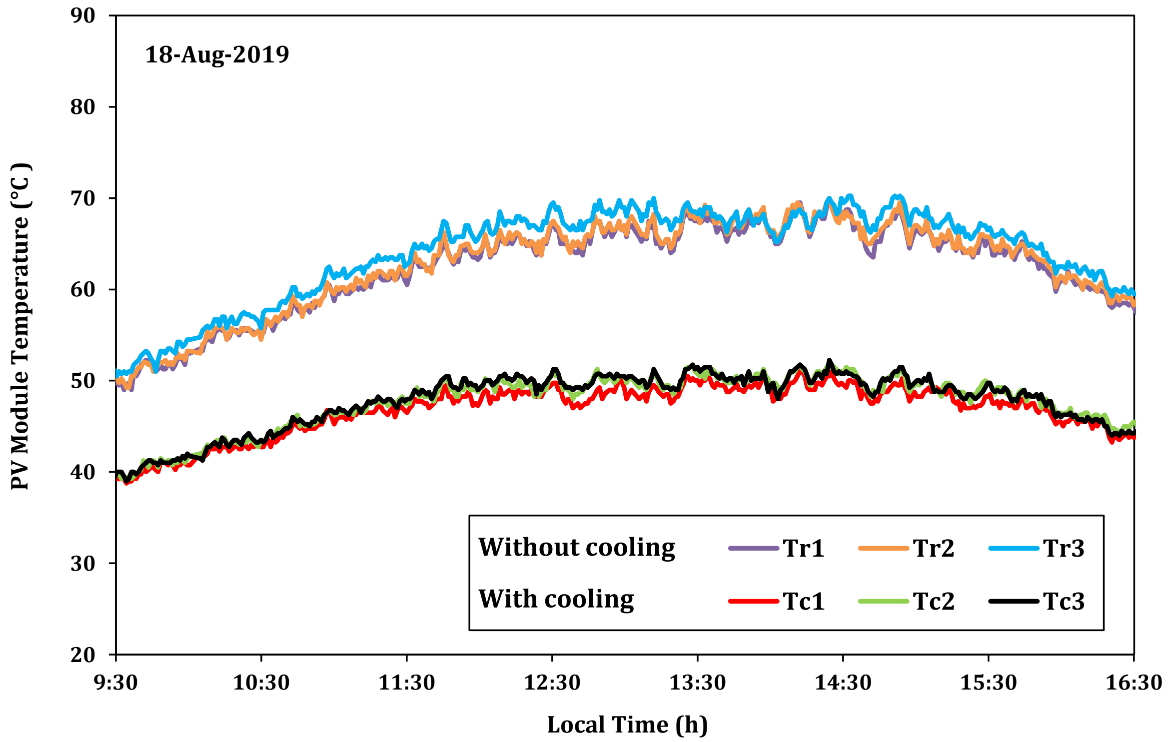


Figure 4-11 Temperatures of the cooled and reference PV modules (August 18, 2019).

Figure 4-12 displays the instantaneous and the average temperature difference between the reference (without cooling) PV module and the cooled module throughout the day. The figure shows the sharp reduction in module temperature when the cooling system was started (from 8:30 until 9:30). Then, the temperature reduction varied from 13 °C to about 21 °C throughout the day. The average temperature difference between the cooled and the reference modules over the whole day was 17.1 °C, which represents about 26% reduction in operating temperature. It is also clear from the figure that the highest temperatures reduction values were obtained during the period from 12:30 to15:30. This is mainly due to the low humidity values (10%) recorded at the same period because of the ambient temperature increase **Figure 4-13**.

The evaporative cooling efficiency is directly affected by humidity levels in the surrounding environment. Lower values of humidity encourage the process of water evaporation, which enhances the evaporative cooling system efficiency and reduces further the operating temperature of the PV module.

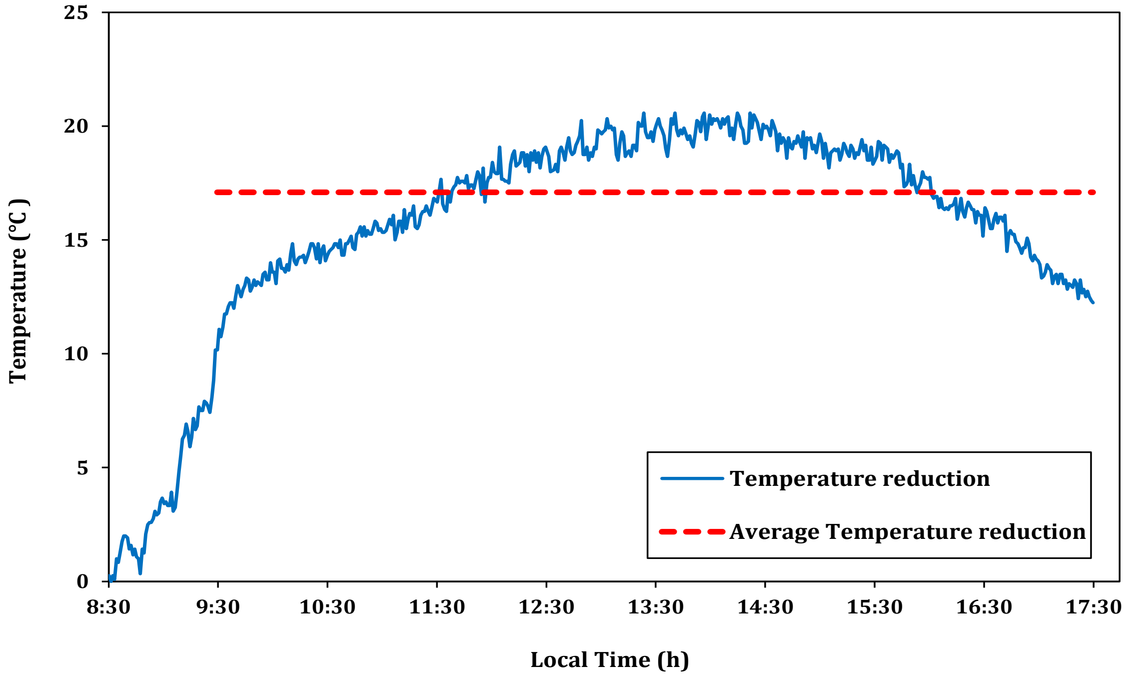


Figure 4-12 Instantaneous and average temperature reduction versus local time.

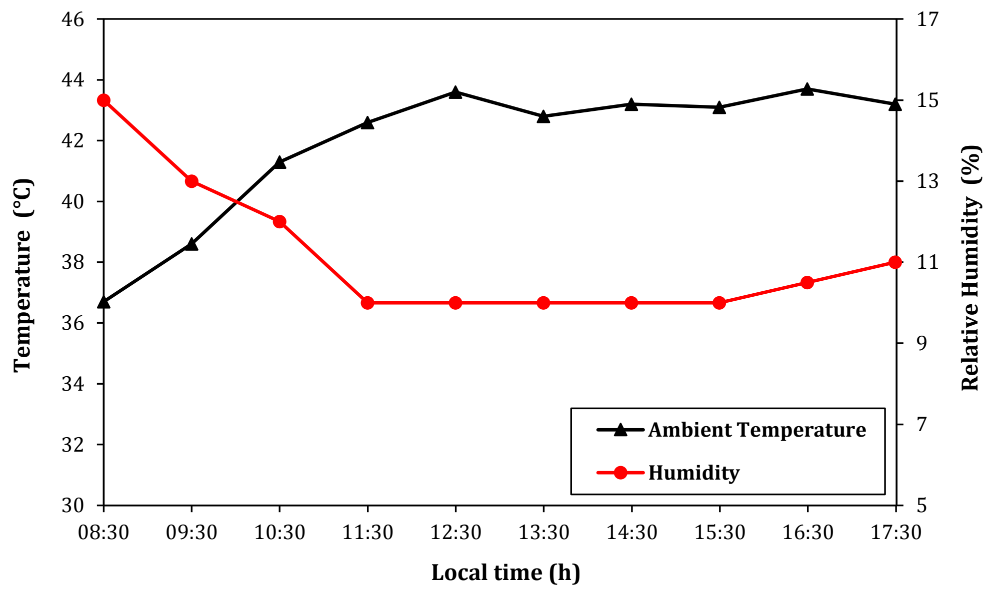


Figure 4-13 Ambient temperature and Humidity variations (August 19, 2019).

3.2. Cooling effect on electrical characteristics

The electrical characteristics of the two tested PV modules (with and without cooling) were measured in terms of current (I) and voltage (V). The output power (P) and electrical efficiency (η) of each module were calculated as follows:

$$P = I \times V \quad (1)$$

$$\eta = \frac{P}{(A \times G)} \quad (2)$$

Where (G) is the incident solar irradiation and (A) is the PV module's surface area.

The variations of short-circuit current (I_{SC}) and open-circuit voltage (V_{OC}) of the modules are shown in **Figure 4-14** and **Figure 4-15**, respectively. As could be seen from **Figure 4-14**, both modules have almost the same short-circuit current values over the day, which indicates that the operating temperature has a negligible effect on the current produced by the module. On the contrary, the open-circuit voltage is strongly affected by the variation of operating temperature. At the beginning of the test, the cooled and the reference modules had the same voltage values. However, after the start of the cooling system, the voltage of the reference module decreased significantly with time due to the increase in the module temperature. While at the same time, the voltage of the cooled one increased and maintained highest values throughout the day **Figure 4-15**. The average V_{OC} improvement over the day was approximately 6.5% due to the use of the evaporative cooling system. This improvement in voltage will contribute significantly in the enhancement of the output power and electrical efficiency of the module.

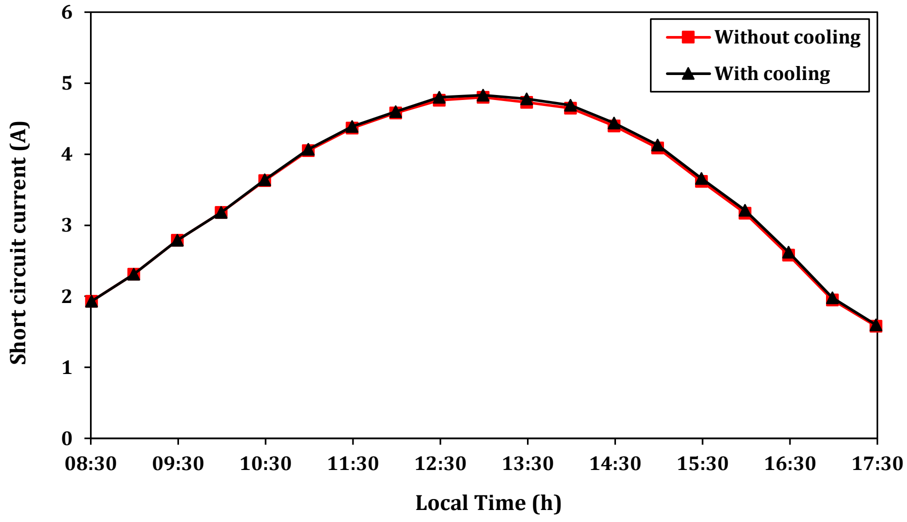


Figure 4-14 Short-circuit current variation of tested PV modules.

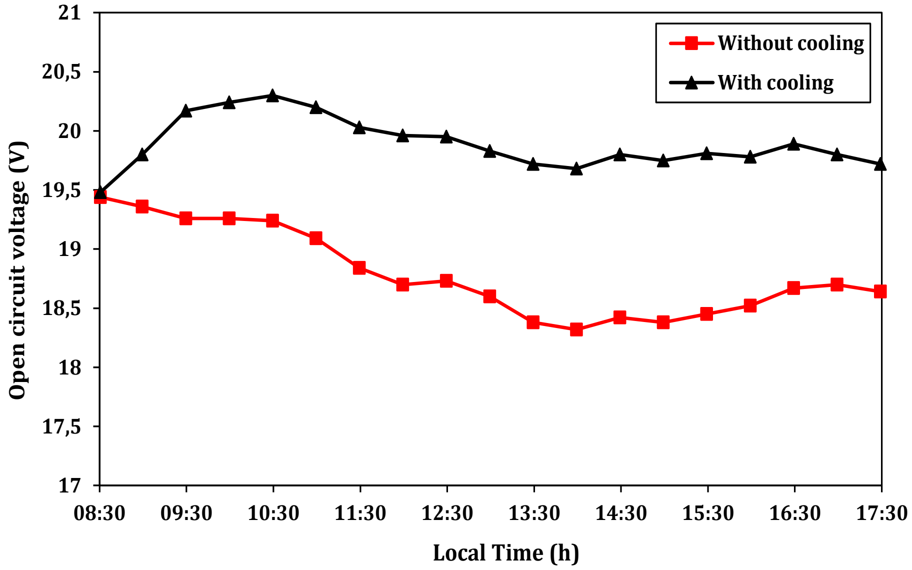


Figure 4-15 Open-circuit voltage variation of tested PV modules.

The output power comparison of both PV modules is illustrated in **Figure 4-16.** At the start of the test, both modules had to some extent the same output power values. However, when the cooling system was started, it was noticed that the output power of the cooled module increased faster than that of the reference one. It is obvious from the figure that the power production of the cooled module was higher than that of the reference one throughout the day.

A maximal output power of 65.07 W was obtained at 13:00 by the cooled PV module against 58.11 W obtained at the same time by the non-cooled module; this represents an increase of about 12% in the energy yield due to the implementation of the cooling system.

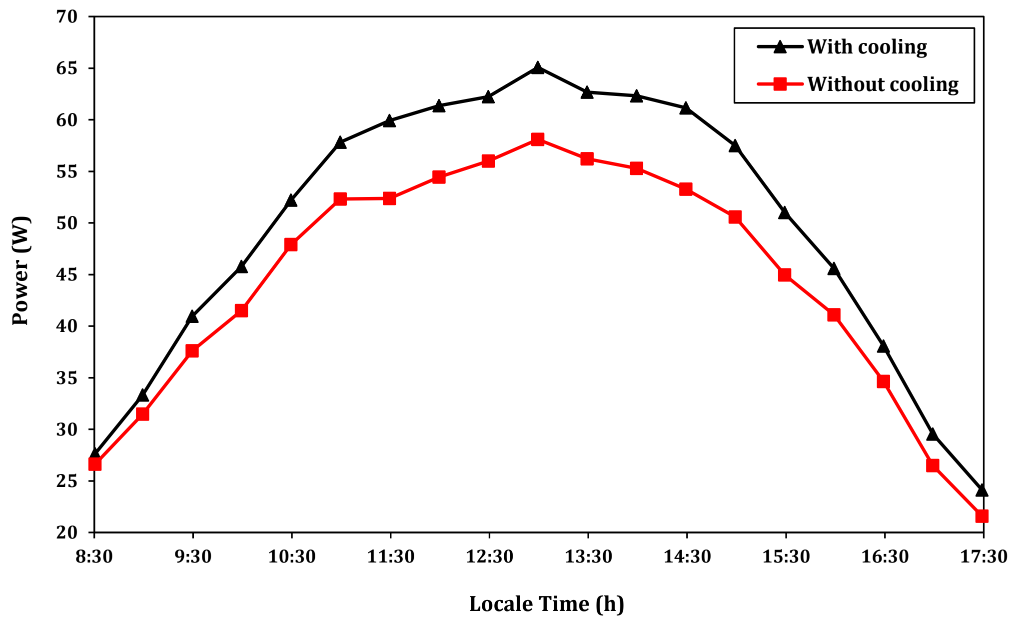


Figure 4-16 Output power variations of tested PV modules.

Figure 4-17 shows the maximal obtained output power of both PV modules and their corresponding operating temperature. The maximum output power of the cooled module was 65.07 W at an operating temperature of 53.5 °C against 58.11 W at 73.25 °C for the reference one. The results presented in the figure are a strong argument of the benefit of using the developed evaporative cooling system based on the capillary action of burlap. The cooling system was able to reduce the operating temperature of the module by more than 20 °C at noon hours where the ambient temperature reached its highest values. This important reduction in the module's operating temperature led to a significant increase of approximately 12% in the output power.

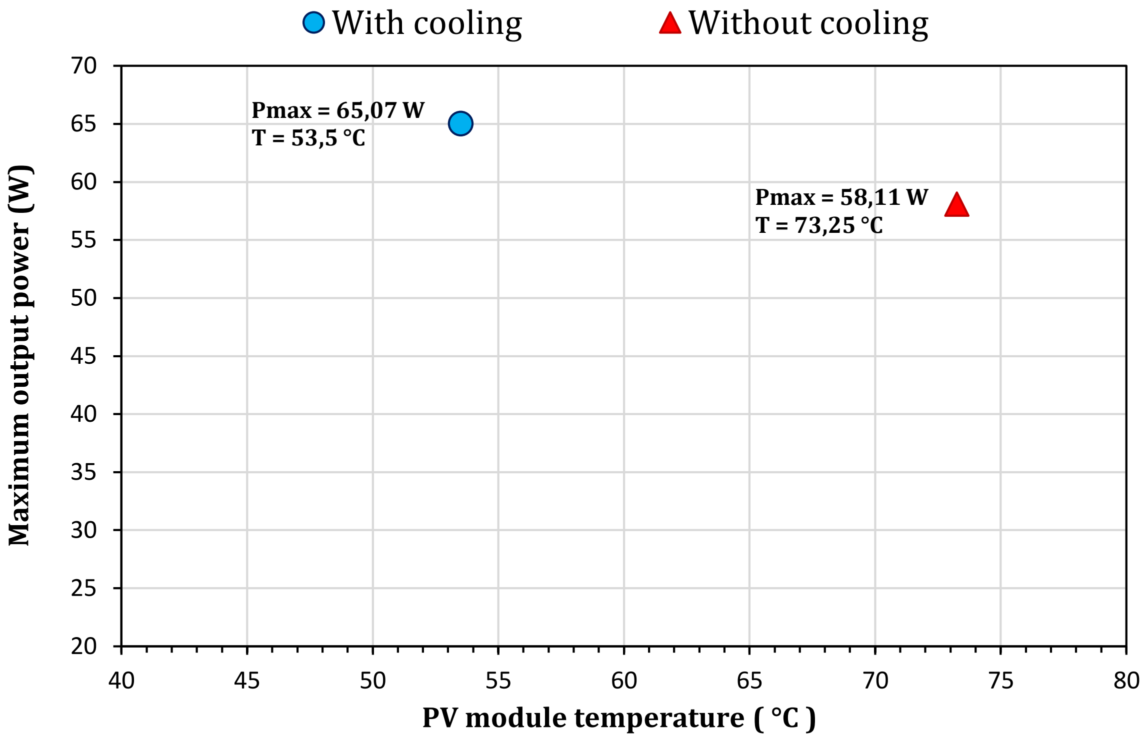


Figure 4-17 Maximum output power versus corresponding operating temperature.

The significant temperature reduction resulted in a striking efficiency improvement as displayed in **Figure 4-18.** It could also be seen from the figure that the electrical efficiency of the cooled PV module showed higher values compared to the module without cooling. The average efficiency of the cooled module over the day was 14.06% against 12.6% for the reference one, which indicates an increase in the electrical efficiency of about 12%. A maximum efficiency improvement by 14.75% was obtained at 14:30. This proves the usefulness of the evaporative cooling system as an effective solution to reduce the PV module temperature and to enhance its performance.

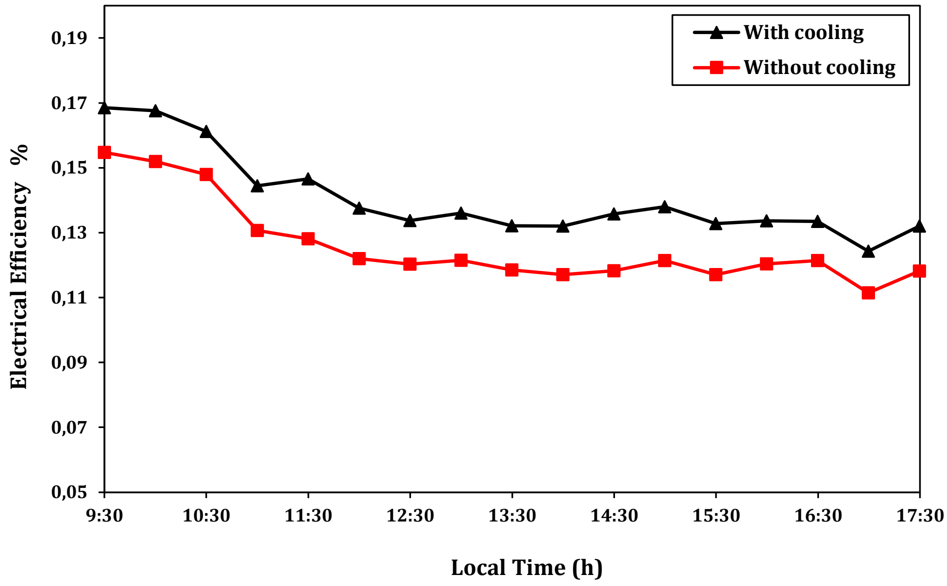


Figure 4-18 Electrical efficiency variations of tested PV modules.

3.3. Water consumption and feasibility aspects

Since the evaporative cooling mechanism is based essentially on water evaporation, water consumption is considered as a major interest, especially in hot and arid areas where water is scarce. In the present study, the water consumption was quantified by the difference between the absorbed and recuperated water quantities during the experimental period as follows:

$$\textit{Water consumption} = (\textit{absorbed water} - \textit{recuperated water}) \tag{3}$$

The cooling system absorbed about 18.3 L of water over the test day (from 8:30 to 17:30). However, 14.8 L was recuperated during the same period, indicating that the cooling system consumed only 0.39 L/h of water. Accordingly, besides the low water consumption, the proposed cooling system accomplished a significant temperature reduction and an electrical efficiency increase of the module, which makes it an attractive and effective cooling solution in hot and arid regions.

Moreover, in the economical view, the proposed cooling system construction does not need high investment cost due to the abundance and the low price of its main components such as the burlap, steel grid and wooden rods. This system is also characterised by its low weight, which will not create any onus on the PV modules or their support.

Table 4-3 shows a comparative analysis of the proposed cooling method in the present study with different techniques presented previously in other research studies where water was used for PV modules cooling either in active or passive systems. Noticeably, the proposed cooling system in this study achieved significant and interesting results in the PV module temperature decrement and efficiency enhancement with lower water consumption compared to the other methods.

Table 4-3 Comparison of the present study results with other researchers studies.

Researcher	**Cooling method**	**Active / Passive**	**Temperature reduction**	**Electrical efficiency improvement**	**Used Water**
(Krauter, 2004)	Film of water over the front surface.	Active	22 °C	10.3 %	Water flow 4.4 $L/min.m^{-2}$
(Abdolzadeh and Ameri, 2009)	Front surface water spray.	Active	23 °C	17 %	Water flow 50 L/h
(Nižetić et al., 2016)	Front and back surface water spray.	Active	32 °C	16.3 %	Water flow 225 L/h
(Chandrasekar and Senthilkumar, 2015)	Evaporative cooling + Heat spreader.	Passive	5.9 °C	14 %	Not mentioned
(Haidar et al., 2018)	Evaporative cooling	Passive	20 °C	10 – 14 %	Water consumption 1 L/h
Present study	Evaporative cooling	Passive	20.6 °C	9 – 14.75 %	Water consumption 0.39 L/h

4. CONCLUSIONS

In this chapter, a passive cooling system has been proposed, fabricated and investigated experimentally under the external climatic conditions of Ouargla city. The cooling system is based on water evaporation and the capillary action of burlap cloth that was attached to the back surface of the PV module.

The obtained experimental results showed that the PV module efficiency is directly related to the operating temperature. The PV conversion efficiency decreases with the temperature increment. The proposed cooling system in this study presented very encouraging results concerning the thermal regulation of PV modules. The operating temperature ranged between 54.2 °C and 76.4 °C with a mean temperature of 66.4 °C for the reference module. Whereas, the cooled module temperature ranged between 44 °C and 55.8 °C with a mean temperature of around 49.3 °C. This corresponds to about 26% temperature reduction. Consequently, an important improvement in the PV module output power and conversion efficiency were achieved. The maximum output power was 58.11 W and 65.07 W for the reference and the cooled modules, respectively, which is equivalent to 12% of output power improvement. Whereas, the maximal efficiency improvement was 14.75%. Moreover, this developed cooling system also helped in maintaining uniform temperature distribution over the module with low water consumption.

GENERAL CONCLUSION

Renewable energy sources are a good alternative to fossil fuels and they have several features, as they are generally less harmful to the environment, no greenhouse gases emission and do not produce waste. They are inexhaustible and they allow decentralised production adapted to both resources and local needs. Moreover, they offer significant energy independence. Recently, the contribution of renewable energies in the energy demand covering has increased significantly. On a global scale, electricity of renewable origin comes from six principle sources distributed as follows: hydropower, wind power, solar (PV and CSP), bio-power and geothermal.

Photovoltaic energy had the most interest and development among all renewable sources due to the high global solar potential, efficiency improvements and important cost decrease of PV cell technologies. However, several factors affect the PV systems conversion efficiency and the power produced from them. These factors can be divided into three main sections: PV cell technology factors, installation type factors and environmental factors.

An in-depth bibliographical research has enabled us to have a general idea about the sensitivity of photovoltaic cells to the environmental factors, especially in arid and desert regions where the climatic conditions are harsh, which limits the efficiency, durability and lifetime of PV conversion systems.

The work presented in this thesis concerns the experimental study and evaluation of weather conditions influence on the performance of PV conversion systems installed in arid and semi-arid areas particularly in the South of Algeria. As well as the contribution to the efficiency improvement of PV systems installed in these areas. Therefore, this experimental work is divided into two main parts; the first part concerns the assessment of power losses due to the dust accumulation, and the second one presents a feasibility investigation of a developed passive cooling system to enhance the PV systems efficiency.

The effect of solar irradiation, dust deposition and sandstorms on the performance of crystalline PV modules installed in Saharan environment was investigated experimentally. Furthermore, the deposited dust characteristics were analysed using an XRF Spectrometer (S1 Titan, trademark: Bruker, USA). The main obtained results showed that:

- The variability in PV systems' performance in South of Algeria was highly dependent on dust accumulation. Both the PV power output and the short circuit current were directly proportional to solar irradiation and inversely proportional to the dust accumulation density.
- An increase in exposure duration under external conditions without (manual or natural) cleaning resulted in significant PV performance degradation due to the increase in deposited dust density.

- Sandstorms led to the deposition of large amount of dust on the PV module's surface, which reduced its performance. Results showed that one sandstorm day reduced the power generation of the SKTM PV power plant by more than 32%.

Moreover, the natural cleaning effect of rainfall was assessed for a whole year exposure period. It was observed that rain falling can contribute in the cleaning of dusty PV modules. However, this method is unreliable considering that rain precipitations are very rare in arid lands.

In order to improve the efficiency of PV modules, a passive cooling system for thermal regulation of PV modules was developed and investigated experimentally under real outdoor hot climate conditions. The cooling system was predicated on water evaporation mechanism in combination with capillary action of an eco-friendly material that was attached directly to the rear surface of the PV module. The main obtained results could be summarised as follows:

- A significant reduction in the temperature was achieved with the help of the developed evaporative cooling system. The mean temperature was 66.4 °C for the reference module. Whereas, the mean temperature of cooled one was around 49.3 °C. This corresponds to about 26% of temperature reduction.

- The developed cooling system was capable of maintaining uniform operating temperature over the module even at the noon period where the ambient temperature was at its highest values. This will contribute strongly to the thermal degradation protection and reliability enhancement of PV systems, especially in hot and arid areas.

- Due to the used cooling system, a considerable enhancement in the PV module output power and conversion efficiency were achieved. The maximum output power improvement was

12%, and the electrical efficiency increment ranged between 9% and 14.75% throughout the day.

The developed cooling system in this work showed high effectiveness in the thermal regulation and efficiency enhancement of the PV modules. Furthermore, this system has many advantages such as being environment-friendly, noiseless, low investment cost and low water consumption.

Finally, it could be concluded that regular cleaning and cooling of PV modules in arid and desert zones is necessary to maintain an optimum performance. Therefore, further techno-economic studies taking into account the geographical and environmental characteristics are recommended to obtain more accurate and reliable results, which could help to develop optimum cleaning and cooling methods in these areas.

REFERENCES

Abd-Elhady, M.S., Serag, Z., Kandil, H.A., 2018. An innovative solution to the overheating problem of PV panels. Energy Convers. Manag. 157, 452–459. https://doi.org/10.1016/j.enconman.2017.12.017

Abderrezek, M., Fathi, M., 2017. Experimental study of the dust effect on photovoltaic panels' energy yield. Sol. Energy 142, 308–320. https://doi.org/10.1016/j.solener.2016.12.040

Abdolzadeh, M., Ameri, M., 2009. Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells. Renew. Energy 34, 91–96. https://doi.org/10.1016/j.renene.2008.03.024

Adinoyi, M.J., Said, S.A.M., 2013. Effect of dust accumulation on the power outputs of solar photovoltaic modules. Renew. Energy 60, 633–636. https://doi.org/10.1016/j.renene.2013.06.014

Agroui, K., 2012. Indoor and outdoor characterizations of photovoltaic module based on mulicrystalline solar cells. Energy Procedia 18, 857–866. https://doi.org/10.1016/j.egypro.2012.05.100

Al-Jawah, M., 2014. A Decision Aiding Framework for Investing in Cleaning Systems for Solar Photovoltaic (PV) Power Plants in Arid Regions. Dissertation. George Washington University.

Amr, A.A. raheim, Hassan, A.A.M., Abdel-Salam, M., El-Sayed, A.H.M., 2019. Enhancement of photovoltaic system performance via passive cooling: Theory versus experiment. Renew. Energy 140, 88–103. https://doi.org/10.1016/j.renene.2019.03.048

Appels, R., Lefevre, B., Herteleer, B., Goverde, H., Beerten, A., Paesen, R., De Medts, K., Driesen, J., Poortmans, J., 2013. Effect of soiling on photovoltaic modules. Sol. Energy 96, 283–291. https://doi.org/10.1016/j.solener.2013.07.017

Appels, R., Muthirayan, B., Beerten, A., Paesen, R., Driesen, J., Poortmans, J., 2012. The effect of dust deposition on photovoltaic modules. Conf. Rec. IEEE Photovolt. Spec. Conf. 1886–1889. https://doi.org/10.1109/PVSC.2012.6317961

Atlas maps, https://nelson.wisc.edu/sage data-and-models/atlas/maps avganntemp/atl_avganntemp_afr.jpg, (Accessed 29/07/2020).

Azeem, M., Boughattas, A., Wiener, J., Havelka, A., 2017. Mechanism of liquid water transport in fabrics; A review. Vlakna a Text. 24, 58–65.

Babatunde, A.A., Abbasoglu, S., Senol, M., 2018. Analysis of the impact of dust , tilt angle and orientation on performance of PV Plants. Renew. Sustain. Energy Rev. 90, 1017–1026. https://doi.org/10.1016/j.rser.2018.03.102

Bahaidarah, H., Subhan, A., Gandhidasan, P., Rehman, S., 2013. Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions. Energy 59, 445–453. https://doi.org/10.1016/j.energy.2013.07.050

Bayod-Rújula, A.A., 2019. Solar photovoltaics (PV), Solar Hydrogen Production: Processes, Systems and Technologies. Elsevier Inc. https://doi.org/10.1016/B978-0-12-814853-2.00008-4

Bechki, D., Bouguettaia, H., Blanco-Galvez, J., Babay, S., Bouchekima, B., Boughali, S., Mahcene, H., 2010. Effect of partial intermittent shading on the performance of a simple basin solar still in south Algeria. Desalination 260, 65–69. https://doi.org/10.1016/j.desal.2010.04.066

Boughali, S., Benmoussa, H., Bouchekima, B., Mennouche, D., Bouguettaia, H., Bechki, D., 2009. Crop drying by indirect active hybrid solar - Electrical dryer in the eastern Algerian Septentrional Sahara. Sol. Energy 83, 2223–2232. https://doi.org/10.1016/j.solener.2009.09.006

Bouraiou, A., Hamouda, M., Chaker, A., Mostefaoui, M., Lachtar, S., Sadok, M., Boutasseta, N., Othmani, M., Issam, A., 2015. Analysis and evaluation of the impact of climatic conditions on the photovoltaic modules performance in the desert environment. Energy Convers. Manag. 106, 1345–1355. https://doi.org/10.1016/j.enconman.2015.10.073

Bouraiou, A., Hamouda, M., Chaker, A., Neçaibia, A., Mostefaoui, M., Boutasseta, N., Ziane, A., Dabou, R., Sahouane, N., Lachtar, S., 2018. Experimental investigation of observed defects in crystalline silicon PV modules under outdoor hot dry climatic conditions in Algeria. Sol. Energy 159, 475–487. https://doi.org/10.1016/j.solener.2017.11.018

BOUTLILIS Fatima, 2018. Modélisation et simulation des sources de production décentralisée Application à l'intégration d'un générateur PV à stockage dans un réseau électrique.Thèse de doctorat, Université Abdelhamid Ibn Badis de Mostaganem.

CEREFE, 2020. Transition Energétique en Algérie Edition 2020.

Chandel, S.S., Agarwal, T., 2017. Review of cooling techniques using phase change materials for enhancing efficiency of photovoltaic power systems. Renew. Sustain. Energy Rev. 73, 1342–1351. https://doi.org/10.1016/j.rser.2017.02.001

Chandrasekar, M., Senthilkumar, T., 2015. Experimental demonstration of enhanced solar energy utilization in flat PV (photovoltaic) modules cooled by heat spreaders in conjunction with cotton wick structures. Energy 90, 1401–1410. https://doi.org/10.1016/j.energy.2015.06.074

Chandrasekar, M., Suresh, S., Senthilkumar, T., Ganesh Karthikeyan, M., 2013. Passive cooling of standalone flat PV module with cotton wick structures. Energy Convers. Manag. 71, 43–50. https://doi.org/10.1016/j.enconman.2013.03.012

Das, B., Das, A., Kothari, V.K., Fanguiero, R., de Araújo, M., 2007. Moisture transmission through textiles: Part I: Processes involved in moisture transmission and the factors at play. Autex Res. J. 7, 100–110.

David Tan, A.K.S., 2011. Handbook for Solar Photovoltaic Systems, Energy Market Authority, Singapore publication.

Dida, M., Boughali, S., Bechki, D., Bouguettaia, H., 2020. Output power loss of crystalline silicon photovoltaic modules due to dust accumulation in Saharan environment. Renew. Sustain. Energy Rev. 124. https://doi.org/10.1016/j.rser.2020.109787

Dittrich, T., 2018. Basic Characteristics and Characterization of Solar Cells. Mater. Concepts Sol. Cells 3–43. https://doi.org/10.1142/9781786344496_0001

Ekpenyong, E.E and Anyasi, F.., 2013. Effect of Shading on Photovoltaic Cell. IOSR J. Electr. Electron. Eng. 8, 01–06. https://doi.org/10.9790/1676-0820106

El-Shobokshy, M.S., Hussein, F.M., 1993. Effect of dust with different physical properties on the performance of photovoltaic cells. Sol. Energy 51, 505–511. https://doi.org/10.1016/0038-092X(93)90135-B

El Chaar, L., Lamont, L.A., El Zein, N., 2011. Review of photovoltaic technologies. Renew. Sustain. Energy Rev. 15, 2165–2175. https://doi.org/10.1016/j.rser.2011.01.004

Elminir, H.K., Ghitas, A.E., Hamid, R.H., El-Hussainy, F., Beheary, M.M., Abdel-Moneim, K.M., 2006. Effect of dust on the transparent cover of solar collectors. Energy Convers. Manag. 47, 3192–3203. https://doi.org/10.1016/j.enconman.2006.02.014

Fathi, M., Abderrezek, M., Friedrich, M., 2017. Reducing dust effects on photovoltaic panels by hydrophobic coating. Clean Technol. Environ. Policy 19, 577–585. https://doi.org/10.1007/s10098-016-1233-9

Fathy, A., 2015. Reliable and efficient approach for mitigating the shading effect onphotovoltaic module based on Modified Artificial Bee Colony algorithm. Renew. Energy 81, 78–88. https://doi.org/10.1016/j.renene.2015.03.017

Fesharaki, V.J., Dehghani, M., Fesharaki, J.J., 2011. The Effect of Temperature on Photovoltaic Cell Efficiency, in: Proceedings of the 1st International Conference on Emerging Trends in Energy Conservation - ETEC Tehran, Tehran, Iran, 20-21 November 2011.

Fouad, M.M., Shihata, L.A., Morgan, E.I., 2017. An integrated review of factors influencing the performance of photovoltaic panels. Renew. Sustain. Energy Rev. 80, 1499–1511. https://doi.org/10.1016/j.rser.2017.05.141

Gharzi, M., Arabhosseini, A., Gholami, Z., Rahmati, M.H., 2020. Progressive cooling technologies of photovoltaic and concentrated photovoltaic modules: A review of fundamentals, thermal aspects, nanotechnology utilization and enhancing performance. Sol. Energy 211, 117–146. https://doi.org/10.1016/j.solener.2020.09.048

Gholami, A., Khazaee, I., Eslami, S., Zandi, M., Akrami, E., 2018. Experimental investigation of dust deposition e ff ects on photo-voltaic output performance. Sol. Energy 159, 346–352. https://doi.org/10.1016/j.solener.2017.11.010

Gouareh, A., 2017. Maîtrise et optimisation de la gestion énergétique en Algérie.Thèse de doctorat, Université Djillali Liabès de Sidi Bel Abbès.

Guan, Y., Zhang, H., Xiao, B., Zhou, Z., Yan, X., 2017. In-situ investigation of the effect of dust deposition on the performance of polycrystalline silicon photovoltaic modules. Renew. Energy 101, 1273–1284. https://doi.org/10.1016/j.renene.2016.10.009

Guo, B., Figgis, B., Javed, W., 2019. Measurement of electrodynamic dust shield efficiency in field conditions. J. Electrostat. 97, 26–30. https://doi.org/10.1016/j.elstat.2018.11.007

Gupta, V., Sharma, M., Pachauri, R.K., Dinesh Babu, K.N., 2019. Comprehensive review on effect of dust on solar photovoltaic system and mitigation techniques. Sol. Energy 191, 596–622. https://doi.org/10.1016/j.solener.2019.08.079

Hachicha, A.A., Al-Sawafta, I., Said, Z., 2019. Impact of dust on the performance of solar photovoltaic (PV) systems under United Arab Emirates weather conditions. Renew. Energy 141, 287–297. https://doi.org/10.1016/j.renene.2019.04.004

Haddad, B., Liazid, A., Ferreira, P., 2017. A multi-criteria approach to rank renewables for the Algerian electricity system. Renew. Energy 107, 462–472. https://doi.org/10.1016/j.renene.2017.01.035

Haidar, Z.A., Orfi, J., Kaneesamkandi, Z., 2018. Experimental investigation of evaporative cooling for enhancing photovoltaic panels efficiency. Results Phys. 11, 690–697. https://doi.org/10.1016/j.rinp.2018.10.016

Hamrouni, N., Jraidi, M., Chérif, a, 2008. Solar radiation and ambient temperature effects on the performances of a PV pumping system. Rev. des Energies Renouvelables 11, 1–95.

Hasan Ali AlBusairi; and Hans Joachim, 2010. PERFORMANCE EVALUATION OF CdTe PV MODULES UNDER NATURAL OUTDOOR CONDITIONS IN KUWAIT, in: 25th European Photovoltaic Solar Energy Conference. pp. 3468–3470.

Hasanuzzaman, M., Malek, A.B.M.A., Islam, M.M., Pandey, A.K., Rahim, N.A., 2016. Global advancement of cooling technologies for PV systems: A review. Sol. Energy 137, 25–45. https://doi.org/10.1016/j.solener.2016.07.010

Hee, J.Y., Kumar, L.V., Danner, A.J., Yang, H., Bhatia, C.S., 2012. The effect of dust on transmission and self-cleaning property of solar panels. Energy Procedia 15, 421–427. https://doi.org/10.1016/j.egypro.2012.02.051

Huang, M.J., Eames, P.C., Norton, B., 2006. Phase change materials for limiting temperature rise in building integrated photovoltaics. Sol. Energy 80, 1121–1130. https://doi.org/10.1016/j.solener.2005.10.006

Ibrahim, I.A., Khatib, T., Mohamed, A., 2017. Optimal sizing of a standalone photovoltaic system for remote housing electrification using numerical algorithm and improved system models. Energy 126, 392–403. https://doi.org/10.1016/j.energy.2017.03.053

IEA, 2020. Key World Energy Statistics 2020.

IEA, https://www.iea.org/reports/tracking-power-2019/solar-pvhttps://www.iea.org/reports/tracking-power-2019/solar-pv, (Accessed 17/04/2020).

Ikkurti, H.P., Saha, S., 2015. A comprehensive techno-economic review of microinverters for Building Integrated Photovoltaics (BIPV). Renew. Sustain. Energy Rev. 47, 997–1006. https://doi.org/10.1016/j.rser.2015.03.081

Ilse, K., Micheli, L., Figgis, B.W., Lange, K., Daßler, D., Hanifi, H., Wolfertstetter, F., Naumann, V., Hagendorf, C., Gottschalg, R., Bagdahn, J., 2019. Techno-Economic Assessment of Soiling Losses and Mitigation Strategies for Solar Power Generation. Joule 3, 2303–2321. https://doi.org/10.1016/j.joule.2019.08.019

IRENA, 2020. Renewable Capacity Statistics 2020.

Islam, M.M., Pandey, A.K., Hasanuzzaman, M., Rahim, N.A., 2016. Recent progresses and achievements in photovoltaic-phase change material technology: A review with special treatment on photovoltaic thermal-phase change material systems. Energy Convers. Manag. 126, 177–204. https://doi.org/10.1016/j.enconman.2016.07.075

Jain-Spark, SOLAR PANEL CLEANING, Jain Irrigation Systems Ltd. Technical report.

Jamil, W.J., Abdul Rahman, H., Shaari, S., Salam, Z., 2017. Performance degradation of photovoltaic power system: Review on mitigation methods. Renew. Sustain. Energy Rev. 67, 876–891. https://doi.org/10.1016/j.rser.2016.09.072

Javed, W., Guo, B., 2020. Effect of relative humidity on dust removal performance of electrodynamic dust shield. J. Electrostat. 105, 103434. https://doi.org/10.1016/j.elstat.2020.103434

Javed, W., Wubulikasimu, Y., Figgis, B., Guo, B., 2017. Characterization of dust accumulated on photovoltaic panels in Doha , Qatar. Sol. Energy 142, 123–135. https://doi.org/10.1016/j.solener.2016.11.053

Jiang, J.A., Wang, J.C., Kuo, K.C., Su, Y.L., Shieh, J.C., Chou, J.J., 2012. Analysis of the junction temperature and thermal characteristics of photovoltaic modules under various operation conditions. Energy 44, 292–301. https://doi.org/10.1016/j.energy.2012.06.029

Johnson, C.E., Srirama, P.K., Sharma, R., Pruessner, K., Zhang, J., Mazumder, M.K., 2005. Effect of particle size distribution on the performance of electrodynamic screens. Conf. Rec. - IAS Annu. Meet. (IEEE Ind. Appl. Soc. 1, 341–345. https://doi.org/10.1109/IAS.2005.1518330

Joshi, P., Arora, S., 2017. Maximum power point tracking methodologies for solar PV systems – A review. Renew. Sustain. Energy Rev. 70, 1154–1177. https://doi.org/10.1016/j.rser.2016.12.019

Ju, X., Xu, C., Han, X., Du, X., Wei, G., Yang, Y., 2017. A review of the concentrated photovoltaic/thermal (CPVT) hybrid solar systems based on the spectral beam splitting technology. Appl. Energy 187, 534–563. https://doi.org/10.1016/j.apenergy.2016.11.087

Kane, A., Verma, V., Singh, B., 2017. Optimization of thermoelectric cooling technology for an active cooling of photovoltaic panel. Renew. Sustain. Energy Rev. 75, 1295–1305. https://doi.org/10.1016/j.rser.2016.11.114

Kant, K., Shukla, A., Sharma, A., Biwole, P.H., 2016. Thermal response of poly-crystalline silicon photovoltaic panels: Numerical simulation and experimental study. Sol. Energy 134, 147–155. https://doi.org/10.1016/j.solener.2016.05.002

Kazem, H.A., Chaichan, M.T., Al-waeli, A.H.A., Sopian, K., 2020. A review of dust accumulation and cleaning methods for solar photovoltaic systems. J. Clean. Prod. 276 123187 .

https://doi.org/10.1016/j.jclepro.2020.123187

Khatib, T., Ibrahim, I.A., Mohamed, A., 2016. A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system. Energy Convers. Manag. 120, 430–448. https://doi.org/10.1016/j.enconman.2016.05.011

Köntges M., Kurtz S., Packard C., Jahn U., Berger K.A., Kato, K., Friesen T., Liu H., Van Iseghem M., 2014. Review of Failures of Photovoltaic Modules Final. Report IEA-PVPS T13-01 2014

Krauter, S., 2004. Increased electrical yield via water flow over the front of photovoltaic panels. Sol. Energy Mater. Sol. Cells 82, 131–137. https://doi.org/10.1016/j.solmat.2004.01.011

Krauter, S.C.W., 2006. Solar Electric Power Generation-Photovoltaic Energy Systems. Springer.

Kreft, W., Filipowicz, M., Żołądek, M., 2020. Reduction of electrical power loss in a photovoltaic chain in conditions of partial shading. Optik (Stuttg). 202, 163559. https://doi.org/10.1016/j.ijleo.2019.163559

Lamont, L.A., El Chaar, L., 2011. Enhancement of a stand-alone photovoltaic system's performance: Reduction of soft and hard shading. Renew. Energy 36, 1306–1310. https://doi.org/10.1016/j.renene.2010.09.018

Luque, A., Hegedus, S., 2011. Handbook of Photovoltaic Science and Engineering, Handbook of Photovoltaic Science and Engineering. https://doi.org/10.1002/9780470974704

Maghami, M.R., Hizam, H., Gomes, C., Radzi, M.A., Rezadad, M.I., Hajighorbani, S., 2016. Power loss due to soiling on solar panel: A review. Renew. Sustain. Energy Rev. 59, 1307–1316. https://doi.org/10.1016/j.rser.2016.01.044

Mahamudul, H., Rahman, M.M., Metselaar, H.S.C., Mekhilef, S., Shezan, S.A., Sohel, R., Abu Karim, S. Bin, Badiuzaman, W.N.I., 2016. Temperature Regulation of Photovoltaic Module Using Phase Change Material: A Numerical Analysis and Experimental Investigation. Int. J. Photoenergy 2016. https://doi.org/10.1155/2016/5917028

Manganiello, P., Balato, M., Vitelli, M., 2015. A Survey on Mismatching and Aging of PV Modules: The Closed Loop. IEEE Trans. Ind. Electron. 62, 7276–7286. https://doi.org/10.1109/TIE.2015.2418731

Mani, M., Pillai, R., 2010. Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations. Renew. Sustain. Energy Rev. 14, 3124–3131. https://doi.org/10.1016/j.rser.2010.07.065

Massi Pavan, A., Mellit, A., De Pieri, D., 2011. The effect of soiling on energy production for large-scale photovoltaic plants. Sol. Energy 85, 1128–1136. https://doi.org/10.1016/j.solener.2011.03.006

Mazón-Hernández, R., García-Cascales, J.R., Vera-García, F., Káiser, A.S., Zamora, B., 2013. Improving the Electrical Parameters of a Photovoltaic Panel by Means of an Induced or Forced Air Stream. Int. J. Photoenergy 2013, 1–10. https://doi.org/10.1155/2013/830968

Mazumder, M., Horenstein, M.N., Stark, J.W., Girouard, P., Sumner, R., Henderson, B., Sadder, O., Hidetaka, I., Biris, A.S., Sharma, R., 2013. Characterization of electrodynamic screen performance for dust removal from solar panels and solar hydrogen generators. IEEE Trans. Ind. Appl. 49, 1793–1800. https://doi.org/10.1109/TIA.2013.2258391

Mekhilef, S., Saidur, R., Kamalisarvestani, M., 2012. Effect of dust, humidity and air velocity on efficiency of photovoltaic cells. Renew. Sustain. Energy Rev. 16, 2920–2925. https://doi.org/10.1016/j.rser.2012.02.012

MEM, Ministry of Energy and Mines.

Mohanty, P., Tyagi, A., 2015. Introduction to Solar Photovoltaic Technology, Food, Energy, and Water: The Chemistry Connection. Elsevier Inc. https://doi.org/10.1016/B978-0-12-800211-7.00012-0

Moharram, K.A., Abd-Elhady, M.S., Kandil, H.A., El-Sherif, H., 2013. Influence of cleaning using water and surfactants on the performance of photovoltaic panels. Energy Convers. Manag. 68, 266–272. https://doi.org/10.1016/j.enconman.2013.01.022

Morales, C., Eriksen, R., Horenstein, M.N., 2017. Increasing Dust Removal Efficiency of Electrodynamic Screens Using Frequency Optimization via COMSOL Multiphysics. Electr. Comput. Eng. Bost. Univ. Boston, MA, USA 2017.

Moreira, H.S., Lucas de Souza Silva, J., Gomes dos Reis, M.V., de Bastos Mesquita, D., Kikumoto de Paula, B.H., Villalva, M.G., 2021. Experimental comparative study of photovoltaic models for uniform and partially shading conditions. Renew. Energy 164, 58–73. https://doi.org/10.1016/j.renene.2020.08.086

Moretón, R., Lorenzo, E., Narvarte, L., 2015. Experimental observations on hot-spots and derived acceptance/rejection criteria. Sol. Energy 118, 28–40. https://doi.org/10.1016/j.solener.2015.05.009

Moshfegh, H., Eslami, M., Hosseini, A., 2018. Thermoelectric cooling of a photovoltaic panel. Green Energy Technol. 625–634. https://doi.org/10.1007/978-3-319-89845-2_44

Mussard, M., Amara, M., 2018. Performance of solar photovoltaic modules under arid climatic conditions: A review. Sol. Energy 174, 409–421. https://doi.org/10.1016/j.solener.2018.08.071

Nadir, N., Bouguettaia, H., Boughali, S., Bechki, D., 2019. Use of a new agricultural product as thermal insulation for solar collector. Renew. Energy 134, 569–578. https://doi.org/10.1016/j.renene.2018.11.054

Najafi, H., Woodbury, K.A., 2013. Optimization of a cooling system based on Peltier effect for photovoltaic cells. Sol. Energy 91, 152–160. https://doi.org/10.1016/j.solener.2013.01.026

Nehari, T., Benlakam, M., Nehari, D., 2016. Effect of the fins length for the passive cooling of the photovoltaic panels. Period. Polytech. Mech. Eng. 60, 89–95. https://doi.org/10.3311/PPme.8571

Nishimoto, S., Bhushan, B., 2013. Bioinspired self-cleaning surfaces with superhydrophobicity, superoleophobicity, and superhydrophilicity. RSC Adv. 3, 671–690. https://doi.org/10.1039/c2ra21260a

Nižetić, S., Čoko, D., Yadav, A., Grubišić-Čabo, F., 2016. Water spray cooling technique applied on a photovoltaic panel: The performance response. Energy Convers. Manag. 108, 287–296. https://doi.org/10.1016/j.enconman.2015.10.079

Nižetić, S., Giama, E., Papadopoulos, A.M., 2018. Comprehensive analysis and general economic-environmental evaluation of cooling techniques for photovoltaic panels, Part II: Active cooling techniques. Energy Convers. Manag. 155, 301–323. https://doi.org/10.1016/j.enconman.2017.10.071

Nižetić, S., Papadopoulos, A.M., Giama, E., 2017. Comprehensive analysis and general economic-environmental evaluation of cooling techniques for photovoltaic panels, Part I: Passive cooling techniques. Energy Convers. Manag. 149, 334–354. https://doi.org/10.1016/j.enconman.2017.07.022

Ogbomo, O.O., Amalu, E.H., Ekere, N.N., Olagbegi, P.O., 2018. Effect of operating temperature on degradation of solder joints in crystalline silicon photovoltaic modules for improved reliability in hot climates. Sol. Energy 170, 682–693. https://doi.org/10.1016/j.solener.2018.06.007

Ogbomo, O.O., Amalu, E.H., Ekere, N.N., Olagbegi, P.O., 2016. A review of photovoltaic module technologies for increased performance in tropical climate. Renew. Sustain. Energy Rev. 0–1. https://doi.org/10.1016/j.rser.2016.11.109

ONM, National Office of Meteorology. Climate data of Ouargla.

Park, Y.B., Im, H., Im, M., Choi, Y.K., 2011. Self-cleaning effect of highly water-repellent microshell structures for solar cell applications. J. Mater. Chem. 21, 633–636. https://doi.org/10.1039/c0jm02463e

Parretta, A., Sarno, A., Vicari, L.R.M., 1998. Effects of solar irradiation conditions on the outdoor performance of photovoltaic modules. Opt. Commun. 153, 153–163. https://doi.org/10.1016/S0030-4018(98)00192-8

Parrott, B., Carrasco Zanini, P., Shehri, A., Kotsovos, K., Gereige, I., 2018. Automated, robotic dry-cleaning of solar panels in Thuwal, Saudi Arabia using a silicone rubber brush. Sol. Energy 171, 526–533. https://doi.org/10.1016/j.solener.2018.06.104

Pearsall, N.M., 2017. Introduction to photovoltaic system performance, The Performance of Photovoltaic (PV) Systems: Modelling, Measurement and Assessment. Elsevier Ltd. https://doi.org/10.1016/B978-1-78242-336-2.00001-X

Qazi, S., 2017. Fundamentals of Standalone Photovoltaic Systems, Standalone Photovoltaic (PV) Systems for Disaster Relief and Remote Areas. https://doi.org/10.1016/b978-0-12-803022-6.00002-2

Rahmouni, S., 2018. Etude prospective de la transition énergétique et l ’ impact environnemental en Algérie. Thèse de doctorat, Université Kasdi Merbah Ouargla

Rajput, U.J., Yang, J., 2018. Comparison of heat sink and water type PV/T collector for polycrystalline photovoltaic panel cooling. Renew. Energy 116, 479–491. https://doi.org/10.1016/j.renene.2017.09.090

Ramli, M.A.M., Prasetyono, E., Wicaksana, R.W., Windarko, N.A., Sedraoui, K., Al-turki, Y.A., 2016. On the investigation of photovoltaic output power reduction due to dust accumulation and weather conditions. Renew. Energy 99, 836–844. https://doi.org/10.1016/j.renene.2016.07.063

Rawat, R., Kaushik, S.C., Lamba, R., 2016. A review on modeling, design methodology and size optimization of photovoltaic based water pumping, standalone and grid connected system. Renew. Sustain. Energy Rev. 57, 1506–1519. https://doi.org/10.1016/j.rser.2015.12.228

Rawat, R., Lamba, R., Kaushik, S.C., 2017. Thermodynamic study of solar photovoltaic energy conversion: An overview. Renew. Sustain. Energy Rev. 71, 630–638. https://doi.org/10.1016/j.rser.2016.12.089

REN21, Renewables 2020 global status report.

Said, S.A.M., Walwil, H.M., 2014. Fundamental studies on dust fouling effects on PV module performance. Sol. Energy 107, 328–337. https://doi.org/10.1016/j.solener.2014.05.048

Saidan, M., Albaali, A.G., Alasis, E., Kaldellis, J.K., 2016. Experimental study on the effect of dust deposition on solar photovoltaic panels in desert environment. Renew. Energy 92, 499–505. https://doi.org/10.1016/j.renene.2016.02.031

Sampaio, P.G.V., González, M.O.A., 2017a. Photovoltaic solar energy: Conceptual framework. Renew. Sustain. Energy Rev. 74, 590–601. https://doi.org/10.1016/j.rser.2017.02.081

Sampaio, P.G.V., González, M.O.A., 2017b. Photovoltaic solar energy: Conceptual framework. Renew. Sustain. Energy Rev. 74, 590–601. https://doi.org/10.1016/j.rser.2017.02.081

Sargunanathan, S., Elango, A., Mohideen, S.T., 2016. Performance enhancement of solar photovoltaic cells using effective cooling methods: A review. Renew. Sustain. Energy Rev. 64, 382–393. https://doi.org/10.1016/j.rser.2016.06.024

Sarver, T., Al-Qaraghuli, A., Kazmerski, L.L., 2013. A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches.

Renew. Sustain. Energy Rev. 22, 698–733. https://doi.org/10.1016/j.rser.2012.12.065

Sato, D., Yamada, N., 2019. Review of photovoltaic module cooling methods and performance evaluation of the radiative cooling method. Renew. Sustain. Energy Rev. 104, 151–166. https://doi.org/10.1016/j.rser.2018.12.051

Sayyah, A., Horenstein, M.N., Mazumder, M.K., 2014. Energy yield loss caused by dust deposition on photovoltaic panels. Sol. Energy 107, 576–604. https://doi.org/10.1016/j.solener.2014.05.030

Selmi, T., Abdul-Niby, M., Alameen, M., 2014. Analysis and investigation of a two-diode solar cell using MATLAB/Simulink. Int. J. Renew. Energy Res. 4, 99–102. https://doi.org/10.20508/ijrer.22742

Settou, B., Settou, N., Gouareh, A., Negrou, B., Mokhtara, C., Messaoudi, D., 2021. A high-resolution geographic information system-analytical hierarchy process-based method for solar PV power plant site selection: a case study Algeria. Clean Technol. Environ. Policy 23, 219–234. https://doi.org/10.1007/s10098-020-01971-3

Shahatha Salim, M., Mohammed Najim, J., Mohammed Salih, Salih, Mohammed Salih, S, 2013. Practical Evaluation of Solar Irradiance Effect on PV Performance. Energy Sci. Technol. 6, 36–40. https://doi.org/10.3968/j.est.1923847920130602.2671

Shima, M., Isomura, M., Wakisaka, K.I., Murata, K., Tanaka, M., 2005. The influence of operation temperature on the output properties of amorphous silicon-related solar cells. Sol. Energy Mater. Sol. Cells 85, 167–175. https://doi.org/10.1016/j.solmat.2004.04.016

Shukla, A.K., Sudhakar, K., Baredar, P., 2016. A comprehensive review on design of building integrated photovoltaic system. Energy Build. 128, 99–110. https://doi.org/10.1016/j.enbuild.2016.06.077

Slaoui, A., Lincot, D., François Guillemoles, J., Escoubas, L., 2017. Photovoltaics: Nanomaterials for Photovoltaic Conversion. Nanotechnol. Energy Sustain. 133–162. https://doi.org/10.1002/9783527696109.ch6

Smith, M.K., Wamser, C.C., James, K.E., Moody, S., Sailor, D.J., Rosenstiel, T.N., 2013. Effects of natural and manual cleaning on photovoltaic output. J. Sol. Energy Eng. Trans. ASME 135, 1–4. https://doi.org/10.1115/1.4023927

Solargis, https://solargis.com/maps-and-gis-data/download/algeria, (Accessed 7 October 2018).

Solheim, H.J., Fjær, H.G., Sørheim, E.A., Foss, S.E., 2013. Measurement and simulation of hot spots in solar cells. Energy Procedia 38, 183–189. https://doi.org/10.1016/j.egypro.2013.07.266

Soliman, A.M.A., Hassan, H., Ookawara, S., 2019. An experimental study of the performance of the solar cell with heat sink cooling system. Energy Procedia 162, 127–135. https://doi.org/10.1016/j.egypro.2019.04.014

Stambouli, A.B., Khiat, Z., Flazi, S., Kitamura, Y., 2012. A review on the renewable energy development in Algeria: Current perspective, energy scenario and sustainability issues. Renew. Sustain. Energy Rev. 16, 4445–4460. https://doi.org/10.1016/j.rser.2012.04.031

Strauss, B., Lisco, F., Bukhari, F., Walls, J.M., Barth, K.L., 2019. Novel Hydrophobic Coatings for Soiling Mitigation in the PV Industry: Durability and Anti-Soiling Demonstrations. Conf. Rec. IEEE Photovolt. Spec. Conf. 2899–2903. https://doi.org/10.1109/PVSC40753.2019.8981166

Tanesab, J., Parlevliet, D., Whale, J., Urmee, T., Pryor, T., 2015. The contribution of dust to performance degradation of PV modules in a temperate climate zone. Sol. Energy 120, 147–157. https://doi.org/10.1016/j.solener.2015.06.052

Teo, J.C., Tan, R.H.G., Mok, V.H., Ramachandaramurthy, V.K., Tan, C.K., 2020. Impact of bypass diode forward voltage on maximum power of a photovoltaic system under partial shading conditions. Energy 191. https://doi.org/10.1016/j.energy.2019.116491

Torres, J.P.N., Nashih, S.K., Fernandes, C.A.F., Leite, J.C., 2018. The effect of shading on photovoltaic solar panels. Energy Syst. 9, 195–208. https://doi.org/10.1007/s12667-016-0225-5

Tsanakas, J.A., Ha, L., Buerhop, C., 2016. Faults and infrared thermographic diagnosis in operating c-Si photovoltaic modules: A review of research and future challenges. Renew. Sustain. Energy Rev. 62, 695–709. https://doi.org/10.1016/j.rser.2016.04.079

Twaha, S., Zhu, J., Yan, Y., Li, B., 2016. A comprehensive review of thermoelectric technology: Materials, applications, modelling and performance improvement. Renew. Sustain. Energy Rev. 65, 698–726. https://doi.org/10.1016/j.rser.2016.07.034

Ubisse, A., Sebitosi, A., 2009. A new topology to mitigate the effect of shading for small photovoltaic installations in rural sub-Saharan Africa. Energy Convers. Manag. 50, 1797–1801. https://doi.org/10.1016/j.enconman.2009.03.016

Wang, Z., Zhou, N., Gong, L., Jiang, M., 2020. Quantitative estimation of mismatch losses in photovoltaic arrays under partial shading conditions. Optik (Stuttg). 203, 163950. https://doi.org/10.1016/j.ijleo.2019.163950

wunderground, https://www.wunderground.com/cat6/Africas-Hottest-Reliably-Measured-Temperature-Record-1243F-Thursday-Algeria, (Accessed 25/07/2020).

Xiao, C., Yu, X., Yang, D., Que, D., 2014. Impact of solar irradiance intensity and temperature on the performance of compensated crystalline silicon solar cells. Sol. Energy Mater. Sol. Cells 128, 427–434. https://doi.org/10.1016/j.solmat.2014.06.018

Xue, J., 2017. Photovoltaic agriculture - New opportunity for photovoltaic applications in China. Renew. Sustain. Energy Rev. 73, 1–9. https://doi.org/10.1016/j.rser.2017.01.098

Yaiche, M.R., Bouhanik, A., Bekkouche, S.M.A., Malek, A., Benouaz, T., 2014. Revised solar maps of Algeria based on sunshine duration. Energy Convers. Manag. 82, 114–123. https://doi.org/10.1016/j.enconman.2014.02.063

Yuyi, Z., Yu, Z., Huanxin, L., Yunjia, L., Liang, L., 2013. Control system design for a surface cleaning robot: Regular paper. Int. J. Adv. Robot. Syst. 10, 1–5. https://doi.org/10.5772/56200

Zeki Ahmed Darwish, Hussein A.Kazem, K.Sopian, M.A.Al-Goul, Hussain Alawadhi, 2015. Effect of dust pollutant type on photovoltaic performance. Renew. Sustain. Energy Rev. 41, 735–744. https://doi.org/10.1016/j.rser.2014.08.068

Zhang, L. zhi, Pan, A. jian, Cai, R. rong, Lu, H., 2019. Indoor experiments of dust deposition reduction on solar cell covering glass by transparent super-hydrophobic coating with different tilt angles. Sol. Energy 188, 1146–1155. https://doi.org/10.1016/j.solener.2019.07.026

Zhao, B., Hu, M., Ao, X., Pei, G., 2018. Performance analysis of enhanced radiative cooling of solar cells based on a commercial silicon photovoltaic module. Sol. Energy 176, 248–255. https://doi.org/10.1016/j.solener.2018.10.043

Zhen, J., Yang, Z., 2012. Design and realization of a flat surface cleaning robot. Adv. Mater. Res. 505, 477–483. https://doi.org/10.4028/www.scientific.net/AMR.505.477

Zorrilla-Casanova, J., Piliougine, M., Carretero, J., Bernaola, P., Carpena, P., Mora-Lopez, L., Sidrach-de-Cardona, M., 2011. Analysis of Dust Losses in Photovoltaic Modules. Proc. World Renew. Energy Congr. – Sweden, 8–13 May, 2011, Linköping, Sweden 57, 2985–2992. https://doi.org/10.3384/ecp110572985

ABSTRACT

The work presented in this thesis provides an experimental study of the two most important environmental factors affecting on the performance of photovoltaic systems in arid and desert regions, which are dust accumulation and high ambient temperatures. In this regard, a series of experiments were carried out in order to evaluate the effect of these two factors under the outdoor climatic conditions of Ouargla region in the south of Algeria.

In the first part of experiments, the effect of solar irradiation intensity, accumulation of dust and sandstorms were studied. The obtained experimental results showed that dust deposition on the surface of photovoltaic panels leads to a significant deterioration of their efficiency, this deterioration increases with the increasing of the accumulated dust amount. Due to the dust accumulation, the performance of a PV module decreased by 19% during the exposure period of autumn season. While, the performance of a PV power plant (30 MW) decreased by 32% after a sandstorm day.

In the second part of the experiments, we proposed a passive cooling system, which is based on water evaporation and the capillary action of burlap cloth that was attached directly to the back surface of the PV module. The obtained experimental results showed the high effectiveness of the proposed cooling system in the reduction of the PV panel temperature by 26% and improve its efficiency by 14.75%. In addition, the proposed cooling system is characterised by its lower cost and lower water consumption compared to all previous cooling technologies. Moreover, it is environmentally friendly and without side effects. This makes it a promising solution for the overheating problem of photovoltaic panels in arid and hot regions.

Keywords: Photovoltaic; Passive cooling; Dust accumulation; Performance improvement; Capillary action.

الملخص

العمل المقدم في هذه الأطروحة يقدم دراسة تجريبية لأكثر عاملين بيئيين تأثيرا على أداء الأنظمة الكهروضوئية في المناطق القاحلة والصحراوية والمتمثلين في تراكم الغبار ودرجة حرارة الجو المرتفعة. سلسلة من التجارب تم إنجازها في هذا الصدد من أجل تقييم تأثير هاذين العاملين تحت الشروط المناخية لمنطقة ورقلة في جنوب الجزائر.

في الجزء الأول من التجارب تم دراسة تأثير شدة الاشعاع وتراكم الغبار والعواصف الرملية. أظهرت النتائج التجريبية المتحصل عليها أن توضع الغبار على سطح الالواح الكهروضوئية يؤدي الى تدهور فعاليتها ويزيد هذا التدهور بزيادة كمية الغبار المترسب. حيث أدى ترسب الغبار الى انخفاض أداء اللوح الكهروضوئي بنسبة 19% خلال فترة تعرض فصل الخريف. بينما انخفض أداء محطة كهروضوئية (30 MW) بنسبة 32% بعد يوم عاصفة رملية.

في الجزء الثاني من التجارب قمنا باقتراح نظام تبريد سلبي يعتمد على تبخر الماء والخاصية الشعرية لقماش الخيش الذي تم تثبيته مباشرة في السطح الخلفي للوح الكهروضوئي. أظهرت النتائج التجريبية القدرة العالية لنظام التبريد المقترح في تخفيض درجة حرارة اللوح الشمسي بنسبة 26% وتحسين فعاليته بنسبة 14.75%. إضافة الى ذلك يتميز نظام التبريد المقترح بثمنه المنخفض واستهلاك منخفض للماء مقارنة بكل تقنيات التبريد السابقة. إضافة الى انه صديق للبيئة ودون اثار جانبية. مما يجعل منه حلا واعدا لمشكل انخفاض الأداء بسبب ارتفاع درجة الحرارة في المناطق القاحلة والحارة.

الكلمات الدالة: الطاقة الكهروضوئية؛ التبريد السلبي؛ تراكم الغبار؛ تحسين الاداء؛ الخاصية الشعيرية.