EXPERIMENTAL INVESTIGATION OF THE EFFECT OF DUST DEPOSITION ON PHOTOVOLTAIC MODULE ENERGY PERFORMANCE

2023
MASTER THESIS
ENERGY SYSTEMS ENGINEERING

Azıza IDRISS WARSAMA

Thesis Advisor
Assoc. Prof. Dr. Selcuk SELIMLI

EXPERIMENTAL INVESTIGATION OF THE EFFECT OF DUST DEPOSITION ON PHOTOVOLTAIC MODULE ENERGY PERFORMANCE

Azıza IDRISS WARSAMA

Thesis Advisor
Assoc. Prof. Dr. Selcuk SELIMLI

T.C.
Karabuk University
Institute of Graduate Programs
Department of Energy Systems Engineering
Prepared as
Master Thesis

KARABUK
July 2023

I certify that in my opinion the thesis submitted by Azıza Idrıss Warsama titled "EXPERIMENTAL INVESTIGATION OF THE EFFECT OF DUST DEPOSITION ON PHOTOVOLTAIC MODULE ENERGY PERFORMANCE" is fully adequate in scope and in quality as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Selçuk SELİMLİ ....
Thesis Advisor, Department of Energy Systems Engineering

This thesis is accepted by the examining committee with a unanimous vote in the Department of Energy Systems Engineering as a Master of Science thesis. July 04, 2023

Examining Committee Members (Institutions)		Signature
Chairman	: Prof. Dr. Mehmet ÖZKAYMAK (YBU)	....
Member	: Assist. Prof. Dr.Abdulmuttalip ŞAHİNASLAN (INU)	....
Member	: Assoc. Prof. Dr. Selçuk SELİMLİ (KBU)	....

The degree of Master of Science by the thesis submitted is approved by the Administrative Board of the Institute of Graduate Programs, Karabuk University.

Prof. Dr. Müslüm KUZU ....
Director of the Institute of Graduate Programs

“I declare that all the information within this thesis has been gathered and presented in accordance with academic regulations and ethical principles and I have according to the requirements of these regulations and principles cited all those which do not originate in this work as well.”

Azıza IDRISS WARSAMA

ABSTRACT

M. Sc. Thesis

EXPERIMENTAL INVESTIGATION OF THE EFFECT OF DUST DEPOSITION ON PHOTOVOLTAIC MODULE ENERGY PERFORMANCE

Azıza IDRISS WARSAMA

Karabuk University
Institute of Graduate Programs
The Department of Energy Systems Engineering

Thesis Advisor:
Assoc. Prof. Dr. Selçuk SELIMLI
July 2023, 56 pages

Nowadays, solar energy has become an important and very beneficial source of our life and for our environment. The photovoltaic panel is the most used technology grace to its accessibility to achieve a clean energy future. The performance of photovoltaic panels is affected by the climatic and environmental conditions of their place of installation. The deposition of dust on the surface of a PV panel is one of the factors that degrades the performance of PV module. PV module temperature has a negative effect on the efficiency of photovoltaic systems, too. In our experimental study, we examine the effect of dust deposition on the electrical and thermal performance of photovoltaic panels. Four identical PV panels (PV1, PV2, PV3 and PV4) of 50 W were experimented at inclined at 40° with respect to the horizontal to better see the degradation of the performance of photovoltaic panels. According to the results of this study, it was found that for 61 μm dust particles, the average powers generated by the PV2, PV3 and PV4 panels were reduced by 18.57%, 30.34% and 45.25%, and the reduction in average electrical efficiency was 2.5%, 4.1% and 6% by reference to the PV1 panel. The exergy efficiencies of PV2, PV3 and PV4 decreased by 2.8%, 4.4% and 6.7% compared to PV1. Comparing with PV1, for 109 μm dust particles, the results showed that the average power degradation generated by the PV2, PV3 and PV4 panels was 13.31%, 20.36% and 26.66% and the reduction in efficiency average electricity was respectively 1.7%, 2.7% and 3.6%. Exergy efficiency reduction was 2%, 2.9%, and 4.2%, respectively.

Key Words : Dust accumulation, PV module, electric power performance, energy efficiency.

Science Code : 92802

ÖZET

Yüksek Lisans Tezi

TOZ BİRİKİMİNİN FOTOVOLTAİK MODÜL ENERJİ PERFORMANSI ÜZERİNDEKİ ETKİSİNİN DENEYSEL ARAŞTIRILMASI

Azıza IDRISS WARSAMA

Karabük Üniversitesi
Lisansüstü Eğitim Enstitüsü
Enerji Sistemleri Mühendisliği Anabilim Dalı

Tez Danışmanı:
Doç. Dr. Selçuk SELIMLI

Temmuz 2023, 56 sayfa

Günümüzde güneş enerjisi, yaşamımız ve çevremiz için önemli ve çok faydalı bir kaynak haline gelmiştir. Fotovoltaik panel, temiz bir enerji geleceği elde etmek için erişilebilirliği açısından en çok kullanılan teknolojidir. Fotovoltaik panellerin performansı, kuruldukları yerin iklim ve çevre koşullarından etkilenir. Bir PV panelin yüzeyinde toz birikmesi, PV panelin performansını düşüren faktörlerden biridir. Deneysel çalışmamızda, toz birikiminin fotovoltaik panellerin elektriksel ve termal performansı üzerindeki etkisini inceledik. Fotovoltaik panellerin performansındaki düşüşü daha iyi görmek için yataya göre 40°'de eğimli olarak 50 W'lık dört özdeş PV paneli (PV1, PV2, PV3 ve PV4) denendi. Bu çalışmanın sonuçlarına göre 61 μm toz partikülleri için PV2, PV3 ve PV4 panellerinin ürettiği ortalama güçlerde %18,57, %30,34 ve %45,25 oranında azalma olduğu ve ortalama elektrik verimliliğinde azalmanın ise PV1 paneline göre %2,5, %4,1, ve %6 olduğubelirlenmiştir. PV2, PV3 ve PV4 ekserji verimleri PV1'e göre 2,8%, 4,4% ve 6,7% azalmıştır. PV1 ile karşılaştırıldığında, 109 µm toz parçacıkları için sonuçlar, PV2, PV3 ve PV4 panelleri tarafından üretilen ortalama güç kaybının sırasıyla %13,31, %20,36 ve %26,66 ve ortalama elektrik verimliliğindeki düşüşün sırasıyla %1,7, %2,7 ve %3,6 olduğunu gösterdi. Ekserji verimliliğinde azalma sırasıyla %2, %2,9 ve %4,2 idi.

Anahtar Kelimeler : Toz birikimi, PV modülü, elektrik gücü performansı, enerji verimliliği.

Bilim Kodu : 92802

ACKNOWLEDGMENT

I thank first and foremost ALLAH Almighty for everything.

I also thank the advisor's Assoc. Prof. Dr Selcuk Selimli for agreeing to supervise me in the design and development of this thesis, who supported me a lot on this thesis, and who offered me all his precious advice, for his active listening, and his availability.

I also address my thanks to the head of the Department of Energy Systems Engineering, Prof. Dr. Mehmet Özkaymak, and his team.

I also warmly and particularly thank my dear parents who have always pushed me to go further since my first thesis and who have supported me in difficult times and who have always believed in me and valued each of my successes. It is thanks to your encouragement, your kindness, and your presence by my side that I succeeded in this respectful work. My dear parents, this thesis is for you. May God reward you with the best reward and give you happiness, health, and success.

Thanks to my brothers and sisters, especially the best big sister Hodan Idriss, for all the material and immaterial help they gave me. I wish them much happiness and success.

Finally, I would like to thank all the people who made themselves available and helped me in my wo.

CONTENTS

Page

Page

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

SYMBOLS AND ABBREVITIONS INDEX

SYMBOLS

A	: Solar radiation effected surface area of PV module
$A_{surface}$	: Heat transfer surface area
η_1	: First law efficiency of thermodynamics
η_2	: Second law efficiency of thermodynamics
F	: The solar radiation
h	: Convectional heat transfer coefficient
I	: The current of PV module
I_{sc}	: Short-circuit current
$P_{electric}$	: Electric power of PV module
P_{lost}	: Lost power of PV module
P_{solar}	: Solar power
ΔT	: Temperature difference
$T_{ambient}$	: Ambient temperature
T_{sun}	: Sun temperature
$T_{surface}$	: Panel surface temperature
V	: The voltage of the PV module
V_{wind}	: Wind speed
V_{oc}	: Open-circuit voltage
$X_{electric}$	: Electric exergy
X_{inlet}	: Inlet exergy
X_{lost}	: Lost exergy
X_{outlet}	: Outlet exergy
X_{solar}	: Solar exergy
$X_{thermal}$	: Thermal exergy

ABBREVITIONS

FF	: Fill factor
PV	: Photovoltaic module
PV1	: Photovoltaic module without dust considered a reference
PV2	: Photovoltaic module deposited by 2g of dust particle
PV3	: Photovoltaic module deposited by 4g of dust particle
PV4	: Photovoltaic module deposited by 6g of dust particle

PART 1
INTRODUCTION

Today, energy is an indispensable and highly demanded factor by humans and is a natural source present everywhere in the environment. Indeed, energy is generally defined as the ability to cause a change in the state of a system to perform work or movement. Energy is conserved in quantity, this means that in any transformation, the total amount of energy in a given system does not change, so it cannot be created or destroyed, it just changes form.

A form of energy can be converted into another form of energy by various processes, such as for example the wind has kinetic energy due to its speed which is transmitted into mechanical energy and then into electrical energy using a device. Energy comes in various forms and is usually expressed in joules (J) per SI unit [1].

- Thermal Energy.
- Kinetic Energy.
- Potential Energy.
- Mechanical energy.
- Chemical Energy.
- Electromagnetic Energy.
- Gravitational Energy.
- Nuclear Energy.

There are two types of energy sources, primary energy which corresponds to the direct use of the initial energy of a product without it being subjected to any transformation process. For example, sunlight is a primary energy. Contrary to secondary energy which undergoes a transformation of one form of energy to use it in another form.

1.1. PRIMARY ENERGY SOURCES

The primary energy source is mainly divided into two broad categories: renewable energy and non-renewable energy. In 2011, oil was the most used source of energy in the world with 31% and the second source was coal with 29% than natural gas which followed with 21%. Global rates of primary energy consumption in 2011 are shown in Figure 1.1 [2].

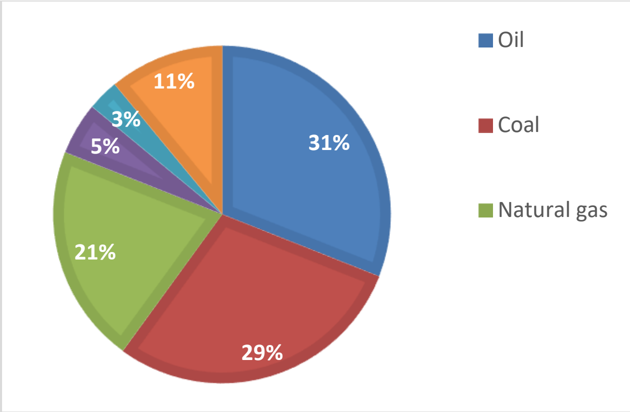


Figure 1. 1. World primary energy consumption [2].

Among the main sources of energy, coal is used in the production of electrical energy in the world in 2013 at 41%, then natural gas which occupies second place with 22% and after hydraulics at 16%. Figure 1.2 represents the distribution of world electricity production by resources [2].

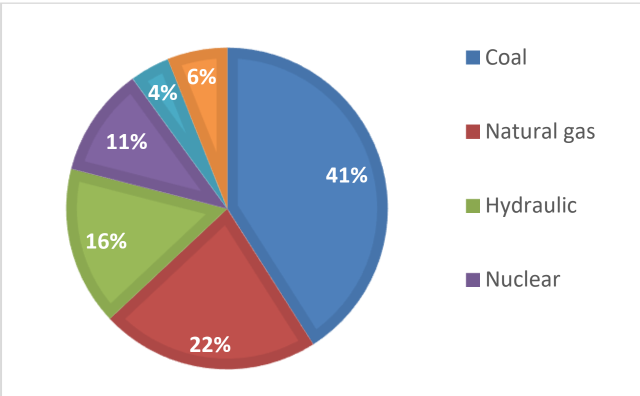


Figure 1. 2. Distribution of world electricity production by resources [2].

At the end of 2016, the estimated consumption of energy resources in the world was 13.147 billion TEP, while Turkey occupied 1% with 126.9 million TEP. The rate of energy sources used in the world in 2016 was 85.5%, these sources contain fossil sources, coal, natural gas, and petroleum. Among these energy sources used in 2016 in the world, oil ranks first with 33.3%, then coal with 28.1%. After coal, natural gas ranks third with 24.1%, followed by hydroelectricity with 6.9% and nuclear energy with 4.5%. The rate of primary energy consumed in the world in 2016 is present in Figure 1.3 [3].

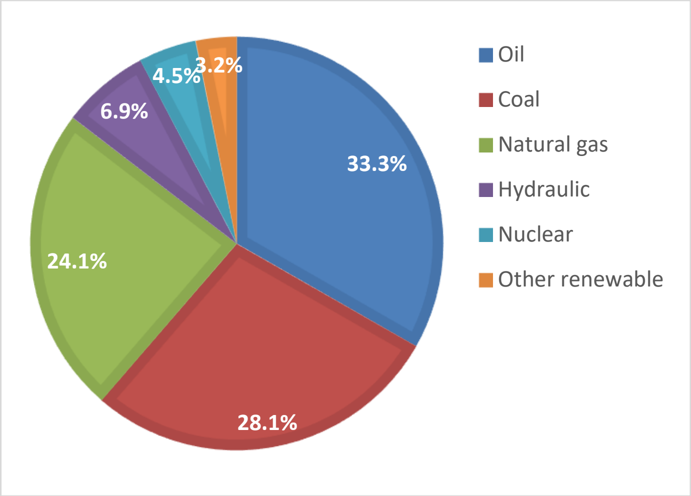


Figure 1. 3. Primary energy consumed in the world in 2016 [3].

In 2011, the rate of primary energy produced in Turkey was as follows: lignite 50%, hydraulic 14%, coal 4% and wind 1%. In Turkey, lignite contained the highest rate in the breakdown of primary energy production in 2016, followed by hydraulic energy rate with 27%. In 2016, Turkey's domestic primary energy supply was 35,374 thousand TEP. Figure 1.4 shows the distribution of primary energy production in Turkey in 2016 [3].

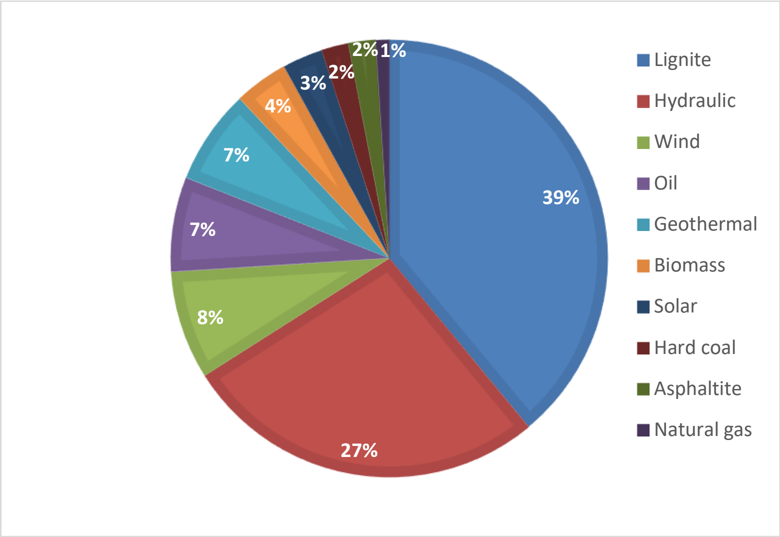


Figure 1. 4. Distribution of primary energy production in Turkey in 2016 [3].

1.1.1. Fossil energy

The world today uses almost 80% of fossil fuels such as natural gas, oil, and coal. These energies are captured by the transformation of organic matter present for many years in the subsoil. And these energies are fossil fuels that contain carbon atoms and underground dioxide. As all energy sources have advantages and disadvantages, fossil fuels have very high efficiency, easy storage, and less occupation of installation space. But their combustion causes the emission of greenhouse gases, the main cause of climate change. But also, their CO2 compositions contribute to air pollution and the release of toxins into the environment, which makes them non-renewable and exhaustible. Fossil fuels are often divided into four parts.

- Petroleum.
- Coal
- Natural Gas.
- Uranium.

1.1.2. Renewable energy

Energy is said to be renewable when it is sustainable, non-polluting, and inexhaustible on a human scale. Renewable energy is clean energy produced by a natural source such as wind, water, and sun, which has benefits in reducing air pollution emissions and plays a very important role in ecology. There are different types of renewable energy.

- Biomass energy.
- Geothermal energy.
- Wind energy.
- Ocean and Sea Energy.
- Hydrogen Energy.
- Hydroelectric Energy.
- Solar Energy.

Hydropower plants are the most preferred among other renewable energy sources in the world with an installed capacity of 1,064.0 GW and a rate of 57.58%. Worldwide, the total installed potential of renewable energy sources is 1,848.0 GW. Wind power plants come second with 433.0 GW of installed capacity and a rate of 23.43%. In contrast, geothermal energy is the source with the lowest installed capacity to obtain electricity in the world. Table 1.1 represented the global installed capacity of renewable energy resources [4].

Table 1. 1. The global installed capacity of renewable energy resources [4].

Type	Capacity (GW)	Rate (%)
Hydraulic	1.064,0	57,58
wind	433,0	23,43
Sun	231,8	12,54
Biomass	106,0	5,74
Geothermal	13,2	0,71
TOTAL	1.848,0	100,0

1.2. SOLAR ENERGY

Solar energy is the radiation emitted into space during the transmutation of the hydrogen gas contained in the heart of the sun into helium. This energy is inexhaustible because it uses the source of the sun which will remain present for millions of years.

Most of the energy sources in the world come from the source of the sun, for example, light energy and heat energy are energy sources that come from the sun [5]. Solar photovoltaic and solar thermal are technologies that offer clear environmental advantages over conventional energy sources, thus enabling the sustainable development of human activities [6]. Solar photovoltaic is a technique that converts sunlight directly into electricity. In contrast, solar thermal is a process that applies heat from the sun to heat homes or generate electricity.

1.2.1. Structure of the sun

The Sun is a star located 150 million kilometers from Earth. It is a fairly homogeneous disc composed essentially of 72% hydrogen and about 26% helium and the remaining 2% being a mixture of other elements such as sodium, carbon, aluminum, nitrogen, potassium, oxygen, and iron [7].
The following Table 1.2 represents the main characteristics of the sun.

Table 1. 2. The main characteristics of the sun [7].

Characteristics	Value
Mass	2× 1030kg
Diameter	1.39× 109m
Radius power	3.86× 1026W
Surface temperature	5777K

1.3.SOLAR RADIATION TO EARTH

1.3.1. Solar Radiation

The transfer of energy through electromagnetic waves or photons transmitted to the effect of displacement in the electronic configuration of molecules or atoms of the body is radiation. Thermal radiation is the radiation emitted by anybody having a temperature above absolute zero. Since the thermal energy generated because of the fusion reaction in the sun is also emitted, this energy arrives at the earth at the speed of light with a temperature of about 6000 K. The value of solar radiation outside the atmosphere can be assumed to be about 1367 W/m2. This value comes from the fact that the earth is not exactly spherical. The sun's rays do not completely reach the earth, the atmosphere and the clouds retain 20% of this radiation. The increase in temperature and the possibility of living on the earth but also the oceanic agitations and the displacement of the wind are caused by 50% of the sunlight which crosses the atmosphere and arrives at the surface of the earth. On the other hand, 30% of solar irradiance is reflected by the Earth's atmosphere. Solar irradiation arriving at the earth is divided into two forms, direct solar radiation, and diffuse solar radiation [8].

1.3.1.1. Direct Radiation

The part of solar radiation that directly reaches the earth is called direct radiation. On cloudless days, direct radiation is the total radiation on earth which can reach 80% [8].

1.3.1.2. Diffuse Radiation

Indirect radiation is radiation from all directions resulting from the reflection of clouds, particles, water vapor and molecules in the atmosphere. Solar radiation in cloudy weather is totally diffusing radiation. On a sunny day, 15 to 20% of solar radiation is diffuse [8].

1.4. SOLAR ENERGY POTENTIAL IN THE WORLD AND TURKEY

1.4.1. Solar Energy in the World

Biomass, solar energy, and geothermal energy are the renewable energy sources that can be harnessed to provide enough thermal energy to obtain electricity. Among these renewable sources, solar energy has the highest potential in the world. The African continent includes the sunniest spaces on the planet. Africa's concentrated solar power capacity is about 470 petawatt hours (PWh) and it also has 660 petawatt hours (PWh) of photovoltaic energy. Nevertheless, for a territory of 1 km^2 located in countries other than Africa, such a potential is 125 GWh [9]. The classification of solar power generation capacity in 2015 in the world is shown in Table 1.3.

Table 1. 3. The placement of solar power generation capacity in 2015 in the world [9].

World Ranking	Country Name	Total Capacity (MW) in 2015	Installed (MW) in 2015
1	China	43,180	15,130
2	Germany	39,553	1418
3	Japan	33,300	10,000
4	USA	27,400	7260
5	Italy	19,160	700
6	UK	8437	3109
7	Spain	6967	6946
8	France	6680	1020
9	Australia	5049	913
10	India	4680	2048

1.4.2. Solar Energy in the Turkey

Turkey lies between 36 and 42 north latitudes in the world. Turkey forms a rectangle with its long side parallel to the equator, which makes it a very interesting place to take advantage of solar energy. Turkey has 36.5 calories per hour of the annual average value of solar energy per square meter. In Turkey, the region with the longest annual illumination duration is the southeastern Anatolia region with 3000 hours. While the Black Sea region has the lowest sunshine duration with 2000 hours [10]. Table 1.4 shows the distribution of illuminance duration and the solar energy potential in Turkey.

Table 1. 4. The duration of illumination and the potential of solar energy according to the regions of Turkey [10].

REGION	TOTAL SUN ENERGY (kWh/m^2year)	SUNBATHING DURATION (hours/year)
S. EASTERN ANATOLIA	1460	2993
MEDITERRENIAN	1390	2956
EASTERN ANATOLIA	1365	2664
CENTRAL ANATOLIA	1314	2628
AEGEAN	1304	2738
MARMARA	1168	2409
BLACK SEA	1120	1971

Figure 1.5 corresponds to the monthly sunshine hours in Turkey. And we see that the longest sunshine corresponds to the months of July and August, while the month of December and January have very short sunshine.

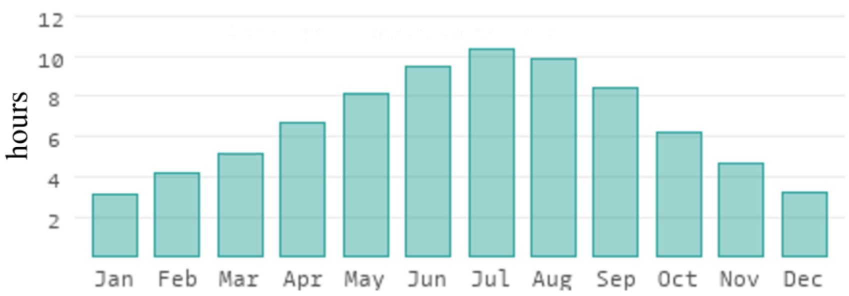


Figure 1. 5. The monthly sunshine hours in Turkey [11].

Turkey's solar energy potential is significant due to its geographical position. Looking at Turkey's energy potential atlas, the total annual sunshine duration is 2737 hours and the total annual incoming solar energy is 1527 MWh $/m^2year$. Figure 1.6 matches the Atlas of Solar Energy Potential in Turkey [5].

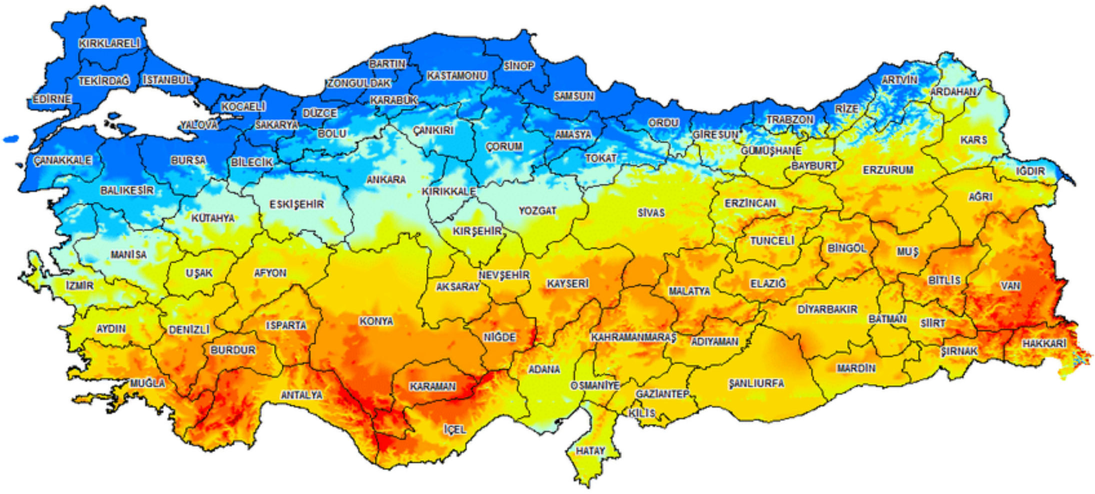


Figure 1. 6. Atlas of solar energy potential in Turkey [12].

1.5. SOLAR ENERGY TECHNOLOGIES AND APPLICATIONS

The solar energy system can be divided into two categories: electricity and heat. The energy captured from solar radiation is either electricity or heat. Solar heat collectors are generally used for hot water collection. And solar cells are essential to produce electricity.

- Electricity - Solar modules: This semiconductor, also called photovoltaic batteries, directly transforms the sun's rays into electricity.
- Heat - Solar thermal systems: In these technologies, heat is recovered from solar energy. This heat can be used directly or used to provide electricity.

Electricity produced from sunlight is done in two different ways, directly and indirectly. In the method of direct electricity generation, thermionic, thermoelectric, and photovoltaic converters are contained. In the indirect transformation into electricity, the steam obtained by using the sun and using a steam or hydrogen cycle produced by solar energy and a thermal electricity generator or a fuel cell are applied [13].

1.6. SOLAR CELL

Photovoltaic cells are semiconductor materials that convert solar energy into electrical energy. The surfaces of the solar cells have the structure of a rectangle, a square or a circle which measures 100 cm^2 and their thickness is of the order of 0.2 to 0.4 mm. Silicon (Si), cadmium sulphide (CdS), gallium arsenic (GaAs) and cadmium tellurium (CdTe) are the substances most frequently used in the manufacture of photovoltaic solar cells. When solar radiation strikes the solar cells, an electrical voltage is created at their ends. From the solar energy that falls on the surface of the cell, the battery produces electrical energy. The yield of solar energy transmuted into electrical energy varies between 5% and 20% [14].

1.7. BRIEF HISTORY

Any device that converts light energy into electricity through the photovoltaic mechanism is a solar cell. The evolution of the solar cell system began in 1839 by the French physicist Antoine-César Becquerel. Becquerel studied the photovoltaic effect by examining a solid electrode in an electrolyte solution when he noticed a voltage forming when light fell on the electrode. In 1883, the first true solar cell was made by Charles Fritts, who made junctions formed by covering selenium with an extremely thin layer of gold. Then in 1941, the silicon solar cell was created by Russell Ohl. The first solar cells had energy transformation efficiencies of less than 1%. Gerald Pearson, Calvin Fuller and Daryl Chapin are the three American researchers who implemented a silicon solar cell in 1954, which offers 6% energy conversion efficiency with direct sunlight [15].

1.8. PV CELL WORKING PRINCIPAL

The principle of operation of solar cells is based on the photovoltaic effect. The photovoltaic effect is a basic physical technique in which sunlight is transformed into electricity by a photovoltaic converter (photovoltaic cell). This effect is formed when photons of sunlight fall on the surface of photovoltaic cells. The word photovoltaic comes from the Greek and is an association of the word photo which means light and voltaic which means voltage. According to Einstein, light is a wave that also behaves like a particle. The characteristic of light is a packet of energy called a photon. In other words, the solar ray is a flow of electromagnetic molecules, of photons. Photons are high energy particles and can cause photo reactions, as in the mechanism of photosynthesis and they are the particle description of electromagnetic light. The energy of electromagnetic light propagates through photons. When the photons reach the surface of the solar cell; Some is reflected, some is absorbed by the cell, and the rest passes through the cell. The photons absorbed by the solar cell produce electricity. Photon energy is transmitted to the electron in the atom of a semiconductor material [16]. The principle of operation of the PV cell is shown in Figure 1.7.

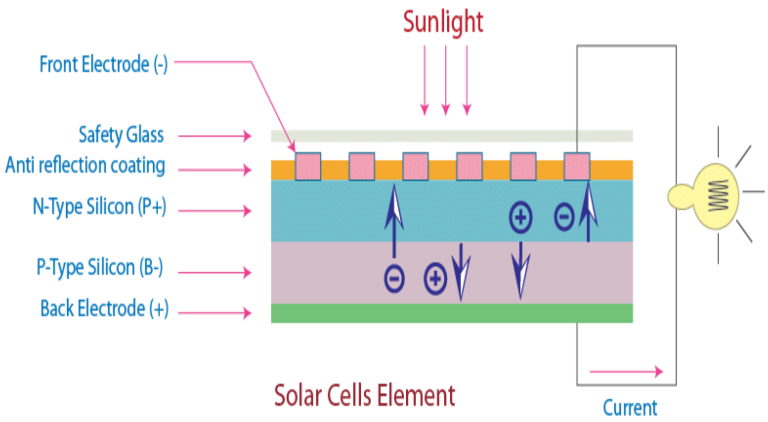


Figure 1. 7. Working principle of PV cell [17].

1.9. STRUCTURE AND TECHNOLOGIES OF PV CELL

Although the photovoltaic cell is an assembly of semiconductor materials, it consists of a junction of two thin layers. These two layers are called negatively charged n-type semiconductors and positively charged p-type semiconductors. The n-type semiconductors contain crystalline silicon, but they are doped with impurities (usually phosphorus) which conduct extra electrons. Similarly, the p-type semiconductor contains crystalline silicon with lots of impurities (mainly boron) which leads to the electron deficient material. Thus, a p-semiconductor has multiples of holes and fewer electrons. The two semiconductors come together to form a pn junction. When this pn junction is illuminated by a light source, the holes flow from the p to n-semiconductor, and the electrons in the opposite direction, forming an electric field [18]. Figure 1.8 shows the composition of the photovoltaic cell.

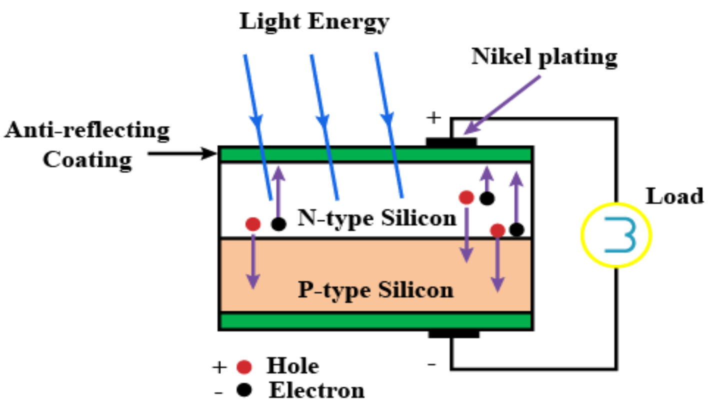


Figure 1. 8. Composition of the photovoltaic cell [19].

Under standard conditions, a specific photovoltaic cell generates about 0.5-0.6 V of voltage and about 3 A of current, which is equivalent to a few watts of power. The solar cells are connected in series to have the desired voltage often around 12-24 V and in parallel to receive the desired current. When several solar cells are connected, they form a module. Similarly, several associated modules form a solar panel, and a set of panels forms a system [18]. The constitution of photovoltaic cells, modules and panels is illustrated in Figure 1.9.

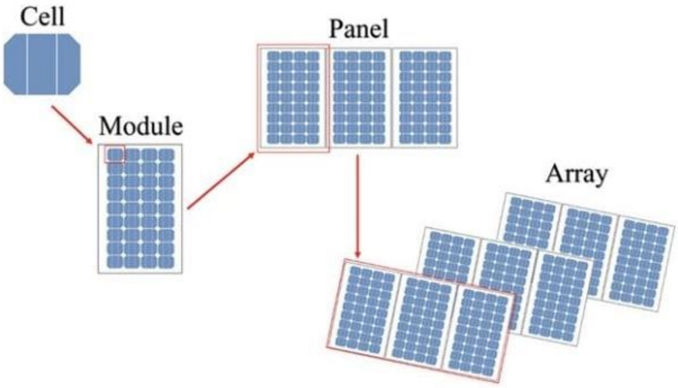


Figure 1. 9. Constitution of photovoltaic cells, modules and panels [20].

Silicon is a raw material for the manufacture of solar cells, and it is present in nature. Depending on their formation processes, photovoltaic cells are named with different names. There are three types of photovoltaic cell generations.

- In this type of generation, it wraps crystalline silicon cells, and they can be divided generally into two categories, monocrystalline and polycrystalline photovoltaic cells. Compared to cells formed by other systems, this type of photovoltaic cell has a longer life and greater efficiency.
- These photovoltaic cells include thin-film technologies and are designed for use on rooftops. These cells are more advantageous because of their ease of transport.
- The third generation are technologies that refer to organic photovoltaic cells [21].

1.10. SOLAR CELL CHARACTERISTICS.

The characteristics that determine the performance of photovoltaic cells are the open-circuit voltage Voc, the short-circuit current Isc, the conversion efficiency η and the fill factor FF. Figure 1.10 represents the I-V curve of a photovoltaic cell and its parameters [22].

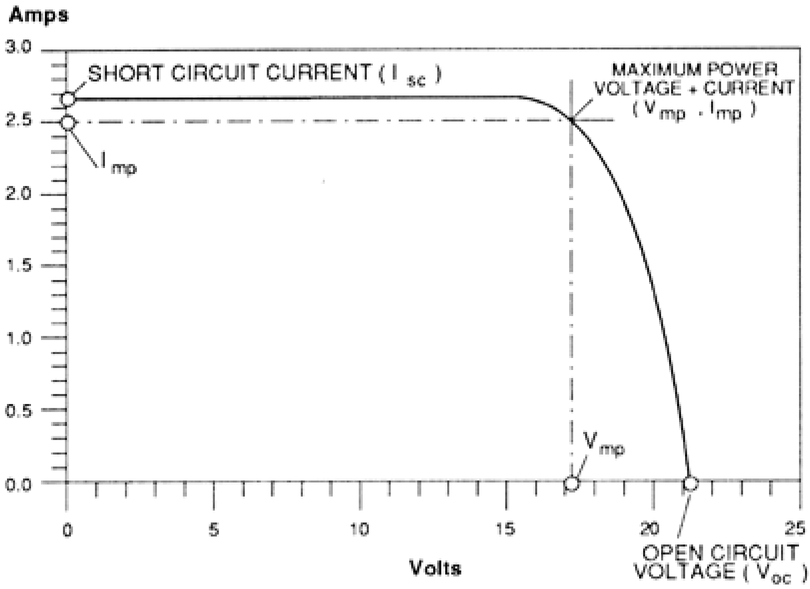


Figure 1. 10. The I-V curve of a photovoltaic cell [23].

- **Open Circuit Voltage**

The maximum possible voltage created at the terminals of a photovoltaic cell when an electric circuit is open, and the electric current of the circuit is equal to zero is called open circuit voltage [22].

- **Short Circuit Current Isc**

The short-circuit current (Isc) is the current that flows when the voltage across the terminals of the photovoltaic cell is zero. Isc is mainly expressed in terms of volume current density and current per unit area in terms of mA/cm^2 [22].

- **Efficiency**

The conversion efficiency of a solar cell is the ratio between the maximum electrical output power (Pm) and the forward power (Pin) [22].

- **Fill Factor**

The fill factor (FF) of a solar cell is determined by the ratio between the maximum power and the ideal power of the cell and is generally expressed in % [22].

1.11. PHOTOVOLTAİCS PANELS

The photovoltaic panel is a device that converts sunlight into electricity. A solar panel comprising solar modules. The advantage of using these panels is to reduce climate change. Solar panels are made up of six components such as photovoltaic solar cells, tempered glass, extruded aluminum frame, encapsulation, polymer back sheet and junction box. The components of a photovoltaic panel are shown in Figure 1.11.

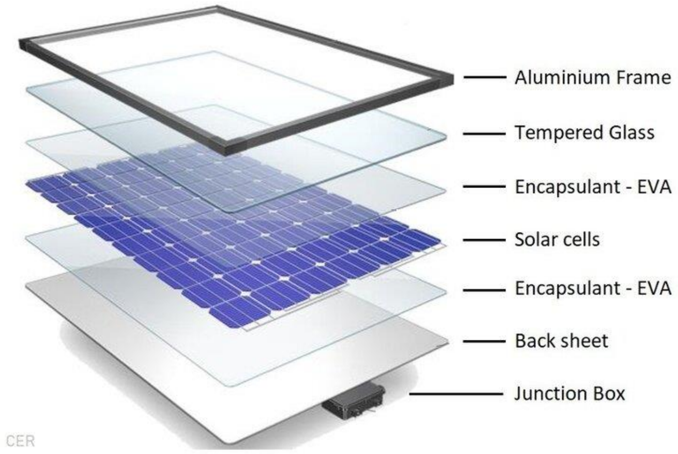


Figure 1. 11. The components of a photovoltaic panel [24].

1.12. TYPES OF PHOTOVOLTAIC PANELS

Photovoltaic panels can be classified mainly into three common types of home solar photovoltaic panels:

- **Monocrystalline PV panels**

Monocrystalline photovoltaic panels are made of monocrystalline silicon in all their plates. These photovoltaic panels have a long lifespan and a better yield which can exceed 20%. But their only drawback is that it is an expensive technique [25].

- **Polycrystalline PV panels**

These types of panels are constructed from polycrystalline silicon. The efficiency of the polycrystalline solar cell is between 15% and 17%. These cells are distinguished by their blue coloration and by their structure. At high temperatures, these panels have a short lifespan. But their production is simpler and cheaper than that of monocrystalline cells [25]. An example of the image of a monocrystalline panel and a polycrystalline one is shown in Figure 1.12.

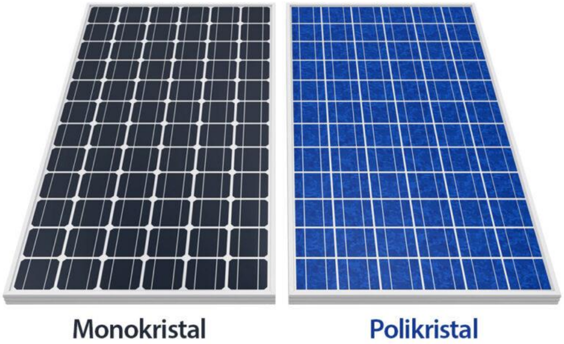


Figure 1. 12. Example of monocrystalline and polycrystalline panel [26].

- **Amorphous silicon solar panels**

Amorphous silicon solar cells are the best photovoltaic cells among thin-film silicon cell groups because they are formed by three layers of film. These cells are usually created from amorphous silicon. Amorphous modules are produced by connecting amorphous cells to each other but with a more disordered structure than normal. Due to their structure, these cells have low efficiency. The image of an amorphous silicon solar panel is shown in Figure 1.13 [25].

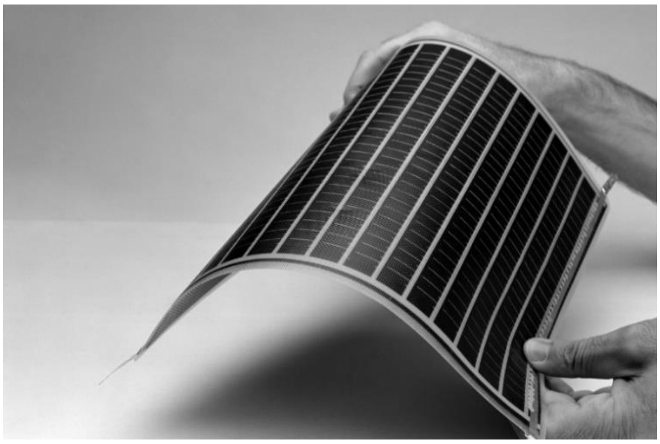


Figure 1. 13. Amorphous silicon cell [27].

1.13. PV SYSTEMS

Photovoltaic systems can be grouped into stand-alone systems and grid connected systems.

- **Stand-alone PV system**

Off-grid photovoltaic systems are mainly composed of a PV generator, a storage battery, a regulator to control the load and AC and DC consumers. These systems are not connected to the electricity grid. The load of an off-grid PV system includes both direct current and alternating current. The system inverter provides an interface between all components of the PV system, providing protection and control. When the power produced by the PV panels exceeds the desired load and when the PV power is restored, the storage battery is insufficient. A PV generator can contain several PV generators [28]. Diagram of the simplified off-grid PV system is illustrated in Figure 1.14.

Figure 1. 14. Diagram of the simplified off-grid PV system [28].

- **Grid-connected PV system**

These types of photovoltaic systems are connected to the local electricity grid. In a grid-connected photovoltaic system, the electricity produced is applied instantly or sold to one of the electricity distribution companies. Grid-connected photovoltaic systems do not need to insert a storage battery [28]. Diagram of the simplified grid-connected PV system is present in Figure 1.15.

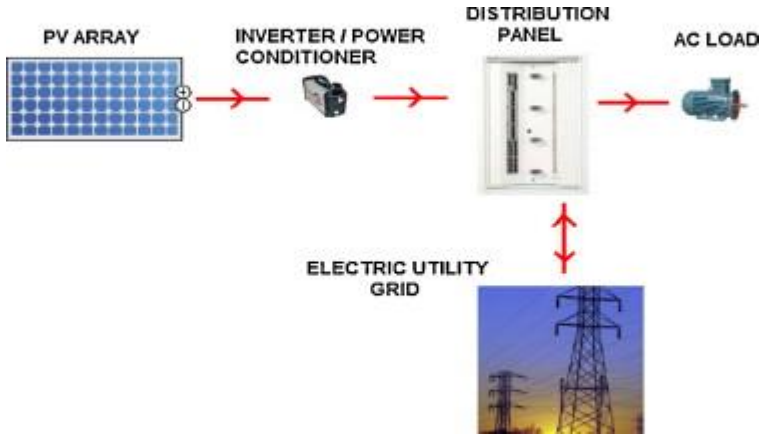


Figure 1. 15. Diagram of the simplified f a grid-connected PV system [28].

1.14. COMPOSITION OF THE SOLAR PHOTOVOLTAIC SYSTEM

The photovoltaic system is composed of solar cells, battery, charge controller, inverter, and lightning protection.

- **Solar cell**

The solar cell captures sunlight and converts it into electrical energy.

- **Battery**

Batteries are used in solar photovoltaic systems to store the electricity produced by the solar modules for use when the solar radiation is not visible, at night or to always supply electrical energy to the load.

- **Charge controller**

The charge controller can automatically prevent the battery from being overcharged and over discharged. And it can determine the use of battery life. A charge controller is an important piece of equipment.

- **Inverter**

The inverter converts direct current into alternating current. Since both solar cells and batteries are DC power sources, an inverter is needed to convert the DC output power of the solar modules into AC current for AC systems.

- **Lightning protection**

System components will be damaged by lightning due to the installation location and environment of the solar PV system. This equipment helps prevent damage caused by lightning. The PV system equipment is shown in Figure 1.16.

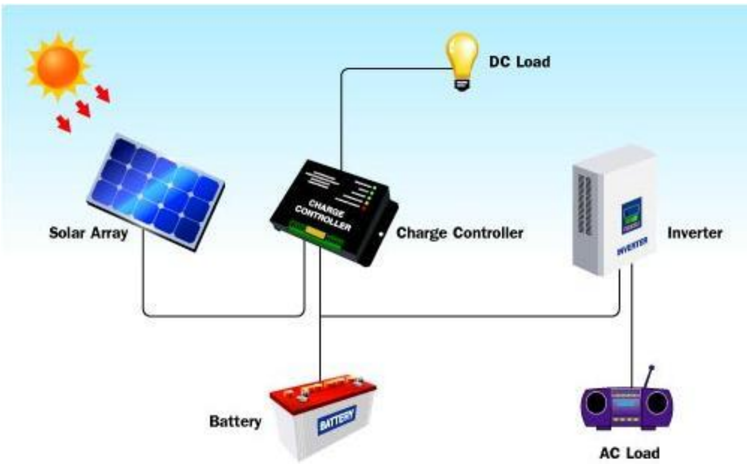


Figure 1. 16. PV system equipments [29].

1.15. FACTORS THAT AFFECT THE PERFORMANCE OF PV SYSTEMS

The electrical performance of photovoltaic panels depends on many factors; solar irradiance, dust accumulation, shading, module temperature, soiling of PV panels and photovoltaic system factors.

- **Solar radiation**

The energy generated by a photovoltaic panel depends on the amount of solar energy reaching the ground. The solar radiation on the photovoltaic panel varies with the location of the panel. The photovoltaic panels receive the maximum radiation when they are perpendicular to the direct radiation. The electric power of the PV panel increases when the solar radiation is high. Similarly, the current of the PV panel varies linearly with the value of the irradiance [30].

- **Dust accumulation**

The accumulation of dust or dirt particles on the surfaces of the photovoltaic panels can block part of the solar radiation, causing a considerable reduction in the power produced[30].

- **Shading**

The shading effect on the photovoltaic modules makes it possible to reduce the output power. Since the cells of the panels are attached in series, the shading does not only influence the current which circulates in the shaded cells, but it also influences the Current flows throughout the module. Shading can be caused by trees, poles or buildings [30].

- **Soiling of PV panels**

The soiling of photovoltaic panels can be caused by dust deposits on their surface. The surfaces of the modules are cleaned by rain. Sometimes the dirt remains even with the heavy precipitation. The lower edge is the most complex part of the modules were, with slight inclinations, dirt forms. The accumulation of dirt causes shading of the cells and thus decreases the power of the panel [30].

- **Module temperature**

A solar cell transforms about 20% of the radiation into electricity and the rest is transformed into heat. Due to excessive temperature and high solar radiation, overheating occurs at the panel. Among the parameters that influence the performance of the panels, the temperature has a great influence on the electrical characteristics of the panels. The open circuit voltage and fill factor decrease linearly with increasing PV cell temperature. Therefore, the decrease in maximum power is caused. But also, factors associated with the components of the PV system can influence the output power of the PV panel, such as the I-V characteristics of the PV panel and the structure of the PV panel. The system inverter also affects the overall performance of the photovoltaic panels [30].

1.16. THESIS OBJECTIVE AND ORGANIZATION

The ultimate objective of this study is to experiment with the influence of the density and size of dust particles on the electrical and thermal performance of PV panels. For this we placed 4 identical photovoltaic panels of 50 W side by side. A clean photovoltaic panel is considered as a reference and the three remaining ones were deposited by dust of different density and thickness.

This thesis has been organized into seven parts. The first part is an introduction to the thesis. The second part includes literature reviews on the subject of this thesis. The third part corresponds to the theoretical basis of the study. The material and the methodology of the practice are developed in the fourth part. Then, the result and the discussion are represented in the fifth part. And finally, the conclusion and summary of the thesis are presented in parts six and seven.

PART 2
LITERATURE REVIEW

To understand the factors that can deteriorate the efficiency and operation of photovoltaic panels. Many experimental studies have been established on the effect of dust, temperature, radiation, and tilt angle on the electrical aspects of PV solar panels.

S. Lasfar, F. Haidara, C. Mayouf et al set up an experimental study on uncleaned polycrystalline photovoltaic panels by comparing with cleaned polycrystalline photovoltaic panels under the climatic conditions of Toujoumine, Nouakchott and Mauritania. And they observed that the output power of dusty module groups decreases by 21.57% [31].

Abhishek Kumar Tripathi, CH.SN. Murthy and M. Aruna experimentally studied a PV module deposited by dust particles of different masses and they found that for 12g of dust, the short circuit current of the panel decreases by 33.33% and the maximum output power is reduced by 42%, while the decrease in open circuit voltage is 6.64% [32].

N. Ketjoy and M. Konyu found out after an experimental study that the solar radiation falling on the PV module decreases with the increase of the dust density on the photovoltaic panel as well as the electric energy production of the PV module is reduced [33].

Abhishek Rao et al also studied the effect of dust on the photovoltaic module. And observed that for a dust density of 7.155 g/m^2, the maximum power reduction is 45-55% of the indoor test. While a density of 1.4 g/m^2 results in a maximum power reduction of 5-6% in the outdoor test [34].

A. Gholami et al examined for 70 days a series of uncleaned panels. And they observed that after 70 days, the dust deposition density is 60986 g/m^2 with a 21.47% decrease in power output [35].

Similarly, M. Katoch, K. Kumar, and V. Dahiya experimented with a dusty panel. And noted that the power attenuation is 38% and 24% for dust densities of 12.5g/m2 at 0° and 10.5g/m^2 at 40° and the decrease in short circuit current is 72 .57% at 0° and 54.06% at 30° [36].

Ahmad Y. Al-Hasan & Adel A. Ghanim have also demonstrated that the reduction of maximum power and short-circuit current is 40% and 30% respectively for an amount of 1.5g/m^2 of dust due to the reduction in light transmission and efficiency of the panel decreases sharply [37].

A. Khodakaram-Tafti and M. Yaghoubi reported during their experimental study that the decrease in the average daily energy consumed by PV panels with tilt angles of 0°, 15°, 30° and 45° was 33.4%, 15.8%, 12.1%, and 11.7%, respectively [38].

Abderrezek and Fathi found power reductions of 10-16% for dust deposition on the bottom edge of photovoltaic panels [39].

Yingya Chen and Al have practically studied the impact of the density and type of dust deposited on polycilisium photovoltaic panels.   but also leads to the formation of hot spots on the photovoltaic panels which affect the efficiency of electricity production [40].

Said and Walwil demonstrated that an amount of 5g/m^2 accumulates on PV modules at an angle of 26° from the horizontal during a period of 45 days and that the transmission of glass decreases by 20% [41].

M. Dida et al, discovered that for a density of 4.36 g/m^2 of dust deposited on the photovoltaic module for 8 weeks, the power maximum output was reduced by 8.41%

and short circuit current dropped by 6.10%, while the reduction in open circuit voltage was 0.51% [42].

A. Juaidi, H.H. Muhammad, R. Abdallah et al evaluated an experimental analysis of uncleaned solar panels for 7 months. And it has been quantified that the power output of uncleaned panels is reduced by 9.99% [43].

R. Dhaouadi, A. Al-Othman, A.A. Aidan et al demonstrated that the dust deposited on the modules led to a reduction in the optical transmission of 30% [44].

In this article the behavior of photovoltaic panels having dust on their surface was studied. The authors indicated that the maximum power of the panels with dust was 42.625 W, while the maximum power of the panels without dust was 77.52 W [45].

Shaharin Anwar Sulaiman et al analyzed the efficiency of photovoltaic panels with dirt or dust under laboratory conditions. And they interpreted that the opaque particles influence the photovoltaic panels a lot [46].

F. Mejia et al certified after their experimental study that the efficiency of the panels during 108 days of dust exposure decreased from 7,2% to 5,6% [47].

S. Ali Sadat et al determined that for dust particles with a thickness of 0.033 g/cm^2, the reduction in maximum electrical power is 98.13%, the short circuit current is reduced by 98.02 % and the open circuit voltage decreases by 20.63%. And they reported that dust not only affects electrical parameters, but also has a significant effect on panel efficiency [48].

After their experimental measurement, M. Saidan et al quantified that when the solar panel is under a one-day dust storm, the solar yield drops by 6.24%, and for a period of one week and one month, the reduction in solar yields is 11.8. % and 18.74% [49].

An experimental study of the effect of dust on the peak power and on the efficiency of the photovoltaic panel was conducted by Shaharin A. Sulaiman, Haizatul H. Hussain, Nik Siti H. Nik Leh and Mohd S. I. Razali. And they indicated that for a very high irradiance, the influence of dust on the electrical performance of the panel is not significant and the peak power decreases to 18% [50].

J. Chen et al also demonstrated in one week that the amount of dust deposited on photovoltaic panels in East China was 0.644 g/m^2 and the output power degradation caused by dust was 7 .4% [51].

Hussain et al studied the impact of depositing different samples of dust particles on a PV module. It was found that the minimum power value was 3.88W for the rice husk deposition on the PV panel [52].

Dayal Singh Rajput et al showed from their experimental work that dust resulted in the reduction of energy produced by 92.11% and efficiency by 89% [53].

From an experimental study, it was found that the accumulation of the plaster dust particle resulted in the reduction of the minimum efficiency of the PV panel by 25.8% with reference to a clean cell [54].

PART 3
THEORETICAL BACKGROUND

Energy analysis of PV module can be defined with the relations given in Eq. (1-4). The energy balance of the PV module is given in Eq. (1).

$$P_{solar} = P_{electric} + P_{lost} \quad (1)$$

In Eq. (1), P_{solar} , $P_{electric}$, P_{lost} are solar, electric, and lost powers from PV module, respectively. Eq. (2) presents solar energy.

$$P_{solar} = FA \quad (2)$$

Where F is the solar radiation and A is the PV module surface area. Eq. (3) is the relation of electrical power, that generated by PV module.

$$P_{electric} = IV \quad (3)$$

Eq. (4) designates the lost power by heat transfer from PV module.

$$P_{lost} = hA_{surface}\,\Delta T \quad (4)$$

Convectional heat transfer coefficient equated as in Eq. (5).

$$h = 3V_{wind} + 2.8 \quad (5)$$

First law efficiency of the PV module can be calculated with the relation by Eq. (6).

$$\eta_1 = \frac{P_{electric}}{P_{solar}} \quad (6)$$

Exergy analysis of PV module can be investigated with the presented relations by Eq. (7-11). Exergy balance of PV module is defined with Eq. (7).

$$X_{solar} = X_{electric} + X_{thermal} + X_{lost} \tag{7}$$

Solar exergy is shown in Eq. (8).

$$X_{solar} = P_{solar} \left[1 - \frac{4}{3}\left(\frac{T_{ambient}}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{ambient}}{T_{sun}}\right)^4\right] \tag{8}$$

Electical exergy is defimed by Eq.(9).

$$X_{electric} = P_{eletric} \tag{9}$$

Thermal exergy of PV module designated with Eq. (10)

$$X_{thermal} = P_{lost}\left(1 - \frac{T_{ambient}}{T_{surface}}\right) \tag{10}$$

Lost exergy visualized in Eq. (11).

$$X_{lost} = X_{solar}(1 - \eta_2) \tag{11}$$

Second law efficiency of PV module is presented in Eq. (12)

$$\eta_2 = \frac{X_{outlet}}{X_{inlet}} \tag{12}$$

PART 4
METHODOLOGY

4.1. ENVIRONNEMTAL CHARACTERITOCS OF THE STUDY AREA

Karabuk Province is in the western Black Sea region of the northern part of Turkey, which has an area of 4,142 km² and is located between 40°57' and 41°34' north latitude and 32° 04' and 33° 06' longitude. While the altitude of the central district is 278 meters, the altitude value rises to 500 meters in the centre of the Safranbolu district. Karabük's solar energy potential is low as it has a lower value than Turkey's average. The annual average value of precipitation in the city of Karabük is 490 mm, and the annual average value of temperature is 13.4˚C. In fact, Karabük is in the Black Sea region with the least solar energy potential. However, when determined specifically for the Black Sea region, there is potential that can be assessed in the southern part of Karabük province [55]. The solar energy potential of Karabük province is shown in Figure 4.1.

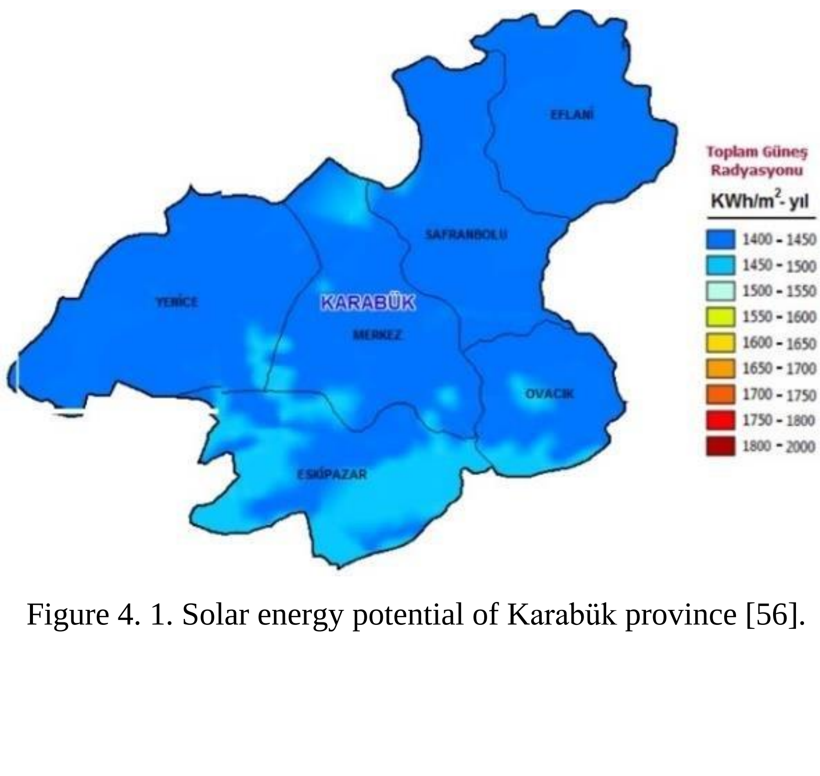


Figure 4. 1. Solar energy potential of Karabük province [56].

4.2. EXPERIMENTAL SETUP AND MEASURING INSTRUMENT

The experimental study is done in front of the workshop of the laboratory of energy systems engineering of the faculty of technology of the university of Karabuk. The tests took place in October 2022 on a clear day between 11:00 and 16:30. The experimental device consisted of four identical polycrystalline silicon photovoltaic panels mounted on a table and inclined at 40° relative to the ground. The specifics of the PV panels are shown in Table 4.1.

Table 4. 1. Specificities of the PV panels .

Peak power (P_{max})	50 W
Voltage for the open circuit condition (V_{oc})	23.80 V
Voltage value for peak power (V_{mp})	20.70 V
Current value for peak power (I_{mp})	2.42 A
Module class	Class A
Current for short circuit case (I_{SC})	2.54A
Size (mm)	430x670

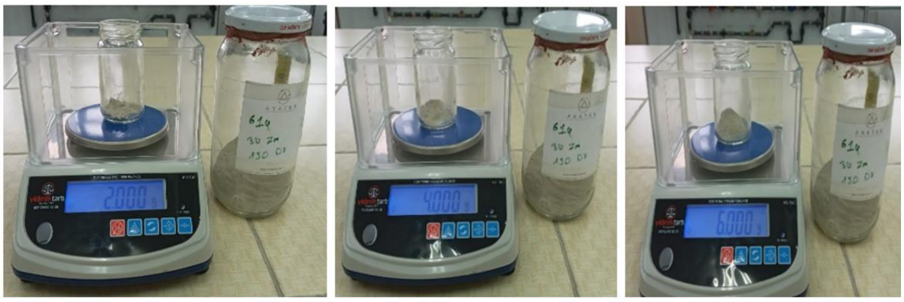
The back surface temperatures of the panels and the ambient temperature were measured using type K thermocouples and were recorded by an Elimko E680 datalogger. The I-V characteristics of the panels were measured using a Dijital DC volt amper meter and then plotted by Microsoft Excel. Solar radiation was followed by a solar power meter. The images of the measuring instruments used are shown in Figure 4.2.

TES 1333R solar power meter   Elimko E680 datalogger   Dijital DC volt amper meter

Figure 4. 2. Measuring instruments.

At the start of the experiment, the preparation of the artificial dusting had been carried out. To have dust particles of 61 μm and 109 μm in thickness. We used steel slag powder, a by-product of steel making, and then we performed a sieving process using sieves with 61 μm and 109 μm openings placed on a sieving machine for 30 minutes. The image of the sieving process is shown in Figure 4.3. For the density measurements of the dust samples, a precision balance was used as shown in Figure 4.4. The dust samples obtained are transferred to saltshakers, to evenly disperse the dust particles on the surface of the panels.

Figure 4. 3. Sieving process.

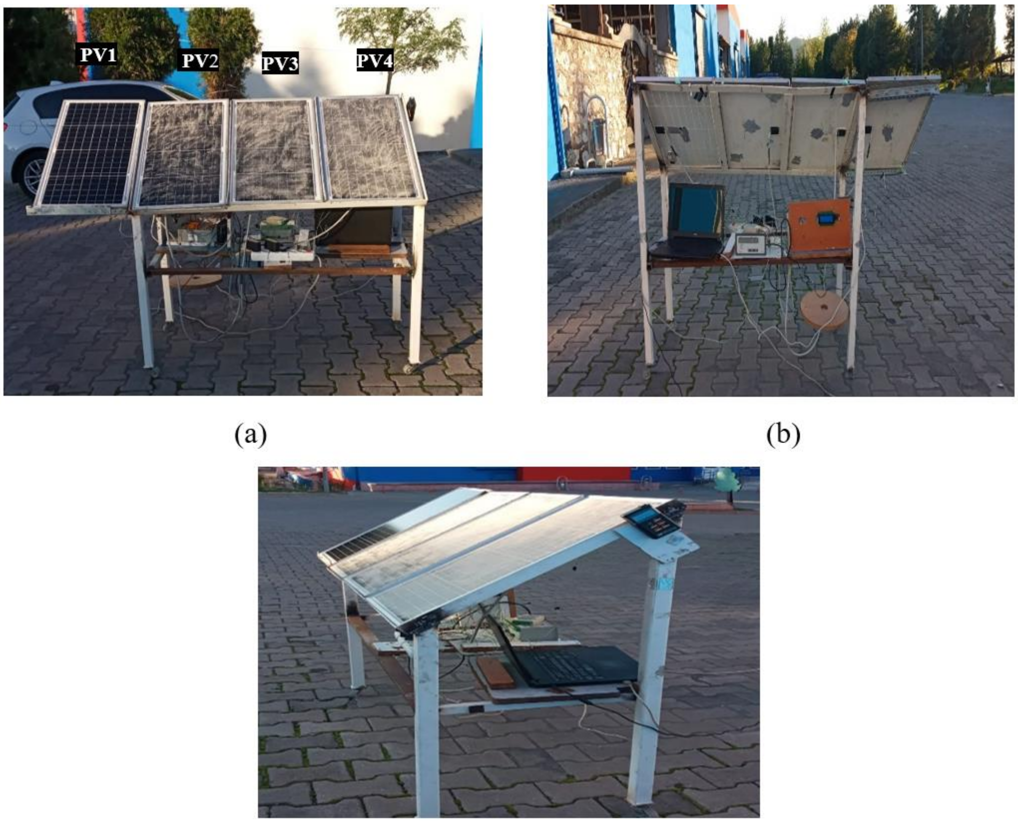


(a)

(b)

Figure 4. 4. Image of quantity measurements of 2 g, 4 g and 6 g dust samples for the a) 61 μm, b) 109 μm thick particle.

For the first day of measurement, in order to determine the electrical and thermal behaviors of the four panels under ambient conditions and deposits of dust particles 61 μm thick, we considered panel PV1 as a reference panel, the panel PV2 is deposited by 2g of dust, panel PV3 is deposited by 4g of dust and panel PV4 is deposited by 6g of dust. The back surface temperatures of the panels and the ambient temperature as well as the I-V characteristics of the panels were evaluated every minute and then we took the average of every half hour to plot their curve. Solar radiation was noted every 5 minutes via a solar power meter then we took the average of every half hour. For the second day of measurement, the procedure is the same as that of the first day except that the dust deposit 61 μm thick is modified by dust particles 109 μm thick. The experimental setup is shown in Figure 4.5 and the images of dust samples used in the experiment scattered on the surface of the panels according to density and particle size are shown in Figure 4.6. The experimental results have been characterized in the following part.



(a) (b)

(c)

Figure 4. 5. Experimental setup views, a) front, b)back, c)side.

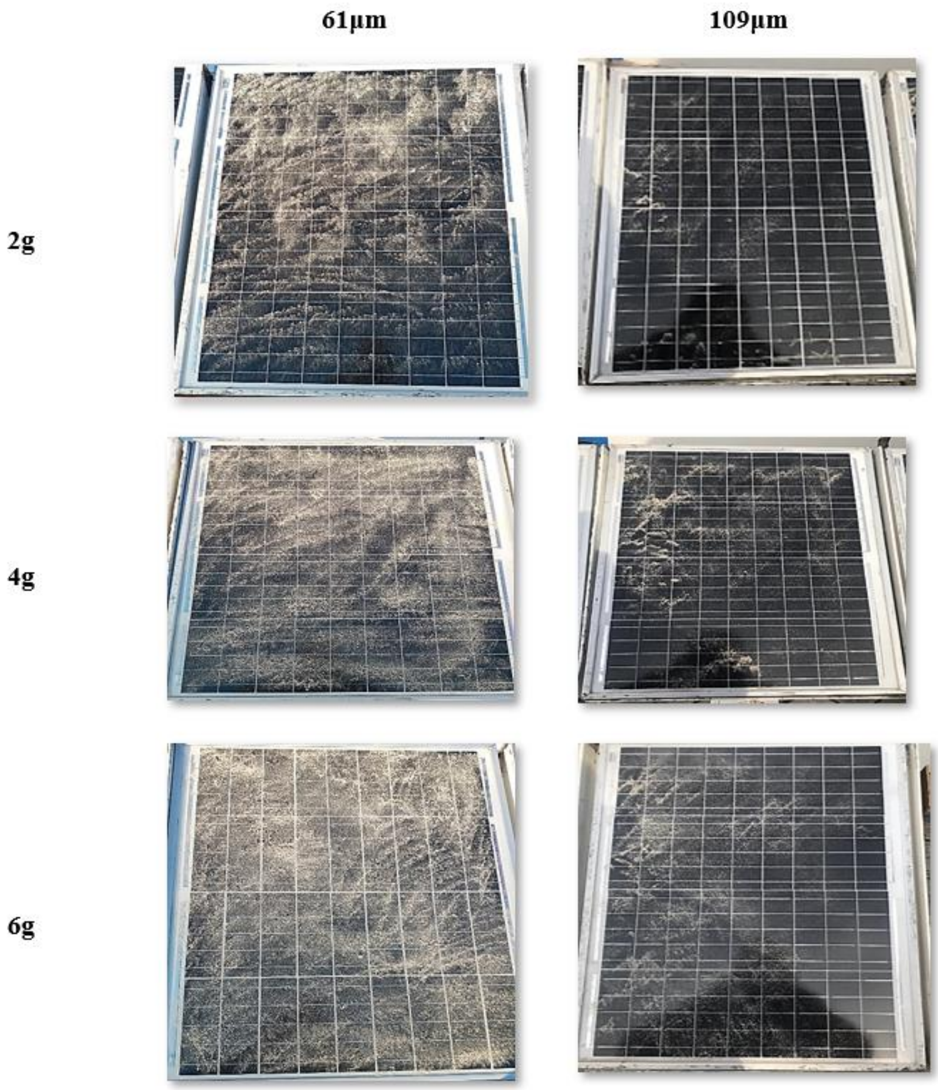


Figure 4. 6. Images of dust samples scattered according to particle size and quantity.

PART 5
RESULTS AND DISCUSSION

5.1. THE EFFECT OF THE 61 µm THICK DUST PARTICLE ON THE ELECTRICAL AND THERMAL CHARACTERISTICS OF PV PANELS.

The arrangement of dust particles is one of the fundamental factors that modify the functionality of photovoltaic panels by affecting their electrical performance. Fine dust particles have more effect on the photovoltaic panel than large particles, because smaller size particles block the sun's rays from reaching the module surface by occupying more space. But also, the increase in the density of dust deposited on the PV modules has the effect of affecting the efficiency of the panels. The influence of dust accumulation on the electrical and thermal properties of PV modules has been analyzed in detail in this part. The parameters measured during the experiment were the current, the voltage and the power of the photovoltaic panels as well as a measurement of the temperature of the panels, of the solar radiation and of the ambient temperature. Figure 5.1 describes the evolution of solar radiation and ambient temperature as a function of time.

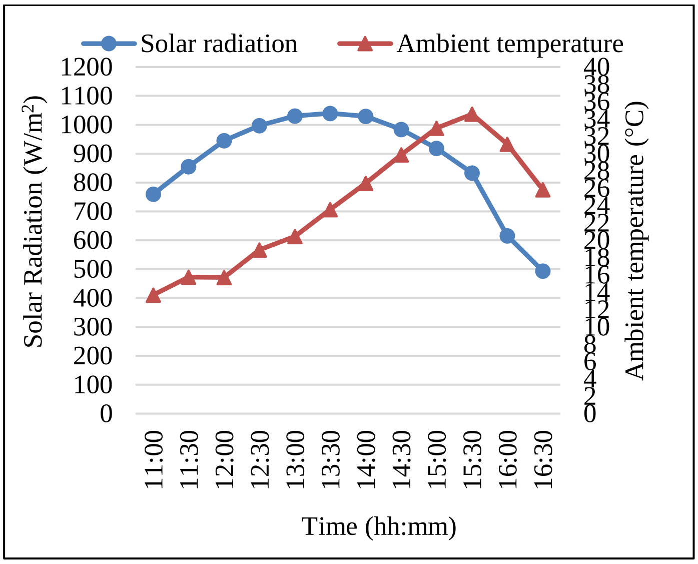


Figure 5. 1. Solar radiation and ambient temperature as a function of time.

According to the curves in Figure 5.1, the solar radiation is equal to a value of 760 W/m^2 and the ambient temperature is equal to 13.70°C at the start of the experimental test. Solar radiation reaches a maximum value of 1039.83 W/m^2 at 13:30, then begins to decrease until it reaches a value of approximately 493.71 W/m^2 at 16:30. While the ambient temperature reached its maximum value of 34.56°C at 15:30. The temporal average values for solar radiation and ambient temperature were 875.32 W/m^2 et 24.09°C. Figure 5.2 illustrated the back surface temperatures of the panels PV.

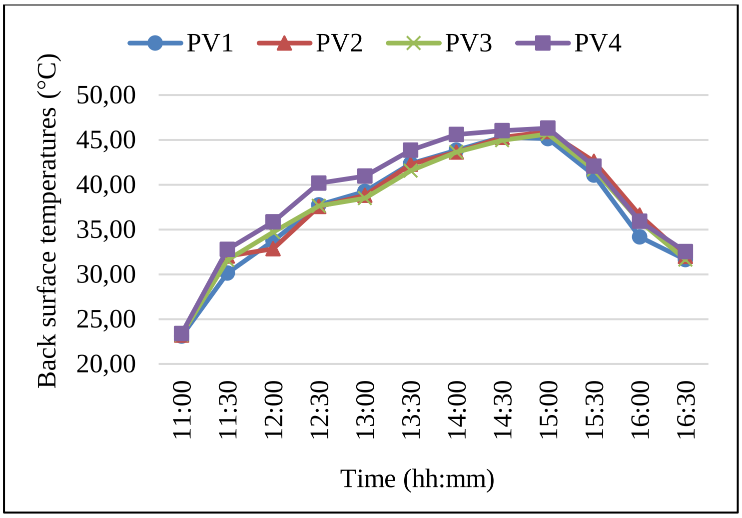
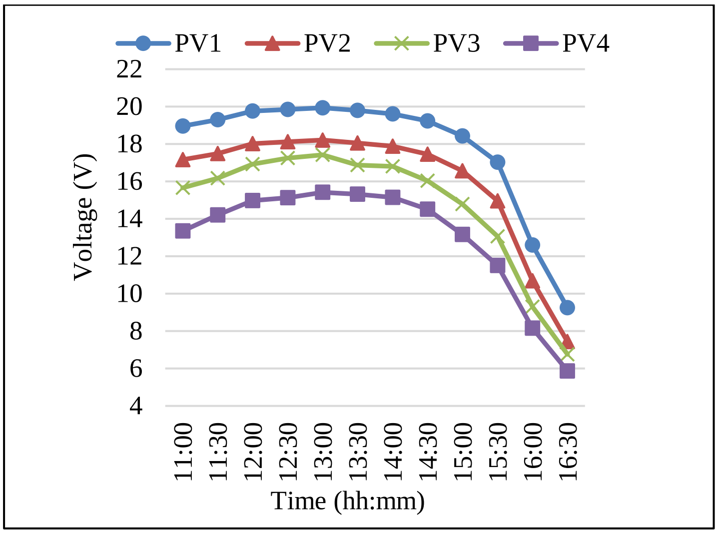
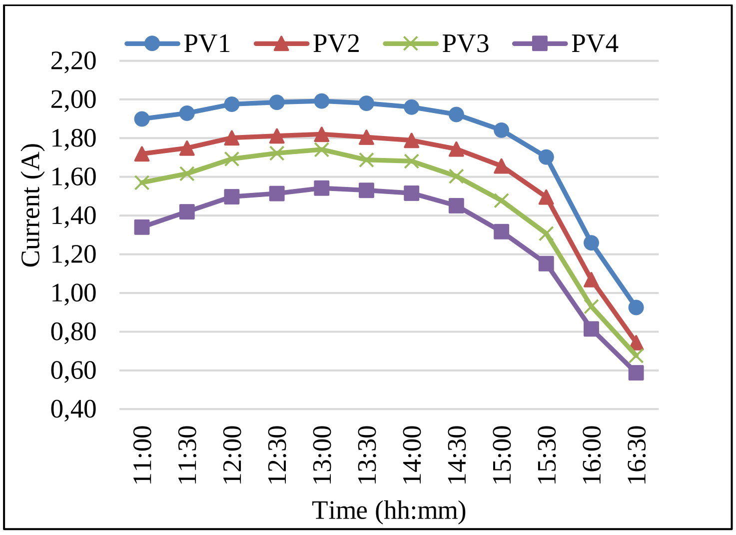


Figure 5. 2. The back surface temperatures of the panels.

Among the curves in Figure 5.2, the curve representing the back surface temperature of the panel PV4 is higher than the curves of the panels (PV1, PV2 and PV3). At 11:00, the values of the back surface temperature of the PV panels were 23.1°C, 23.2°C, 23.25°C and 23.38°C respectively. And at 16:30, these values were 31.64°C, 31.99°C, 31.64°C and 32.52°C respectively. The average back surface temperature values calculated for the four panels were 37.29°C, 37.73°C, 37.56°C and 38.78°C. Figure 5.3(a, b) illustrates the comparison of voltage and current values for the four solar panels (PV1, PV2, PV3 and PV4).



(a)



(b)

Figure 5. 3. (a): Voltage variation curves. (b): Current variation curves.

As illustrated in Figure 5.3(a, b), the voltage, and current curves of the reference panel (PV1) seem much higher than the curves of the PV4 panel compared to the curves of the PV2 and PV3 panels. The maximum voltage values of the four panels measured were respectively 19.94 V, 18.21 V, 17.42 V and 15.42 V at 13:00. And the maximum current values of the four PV panels were 1.99 A, 1.82 A, 1.74 A and 1.54 A respectively. During the experiment, the average voltage values for the four photovoltaic panels (PV1, PV2, PV3 and PV4) were respectively 17.81 V, 16 V, 14.75 V and 13.07 V and the values of average currents were 1.78 A, 1.60 A, 1.48 A and 1.31 A. Figure 5.4 represents the electrical power variation of the PV panels.

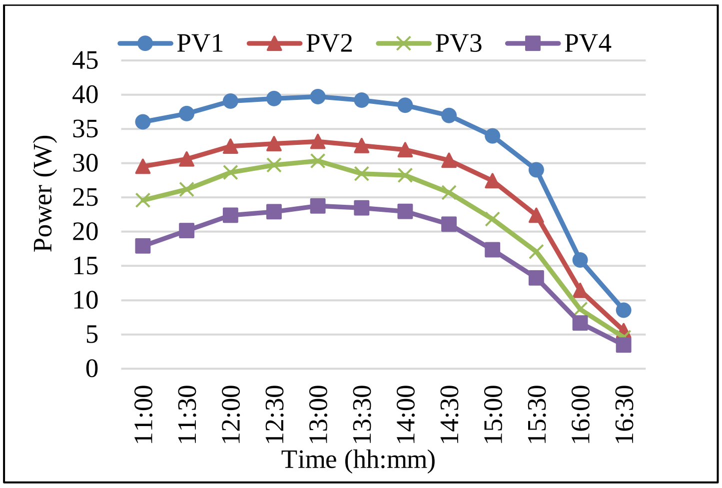


Figure 5. 4. Electrical power variation.

By comparing the curves in Figure 5.4, it has been observed that the power values of the PV4 panel vary between 17.90 W and 3.45 W. While the power values of the reference panel vary between 36.01 W and 8.56 W. This shows us that the power of the PV panels decreases with the increase in the density of dust on their surface. The average electrical powers of four photovoltaic panels were respectively 32.79 W, 26.70 W, 22.84 W and 17.95 W. Figure 5.5 illustrates the relationship between panels electrical efficiency and the density of dust deposited on panels surfaces.

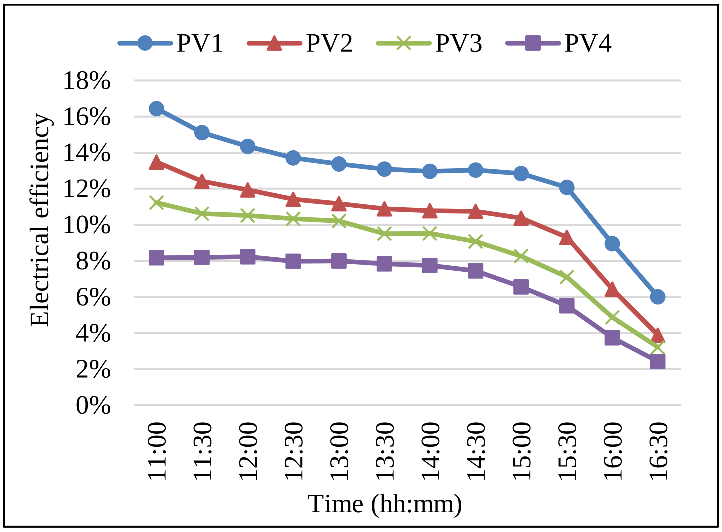


Figure 5. 5. Electrical efficiency of panels.

As shown in Figure 5.5, the electrical efficiency of panel PV1 is 16.4% at 11:00. And for panels PV2, PV3 and PV4, the electrical efficiency was 13.5%, 11.2% and 8.18%

respectively. The average electrical efficiency of the reference panel is 12.8%. And the average electrical efficiency of the PV2, PV3 and PV4 panels are 10.3%, 8.7% and 6.8% respectively. The average electrical efficiency of PV panel 1 is 6% higher than that of the PV4 panel. Solar energy and solar exergy are shown in Fig.5.6.

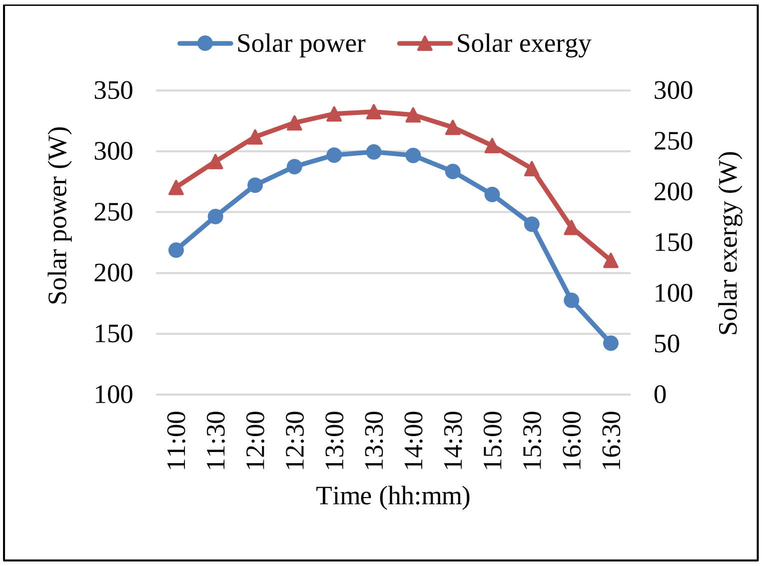


Figure 5. 6. Solar power and Solar exergy.

Looking at the two curves in Fig.5.6, we notice that the solar energy values vary from 218.96 W to 142.24 W between 11:00 and 16:30. While the solar exergy values vary from 204.46 W to 132.42 W. The average value of solar energy was 250.15 W and that of solar exergy was 233 W. The exergy efficiency and the irreversibility of photovoltaic panels are shown in Fig.5.7(a, b).

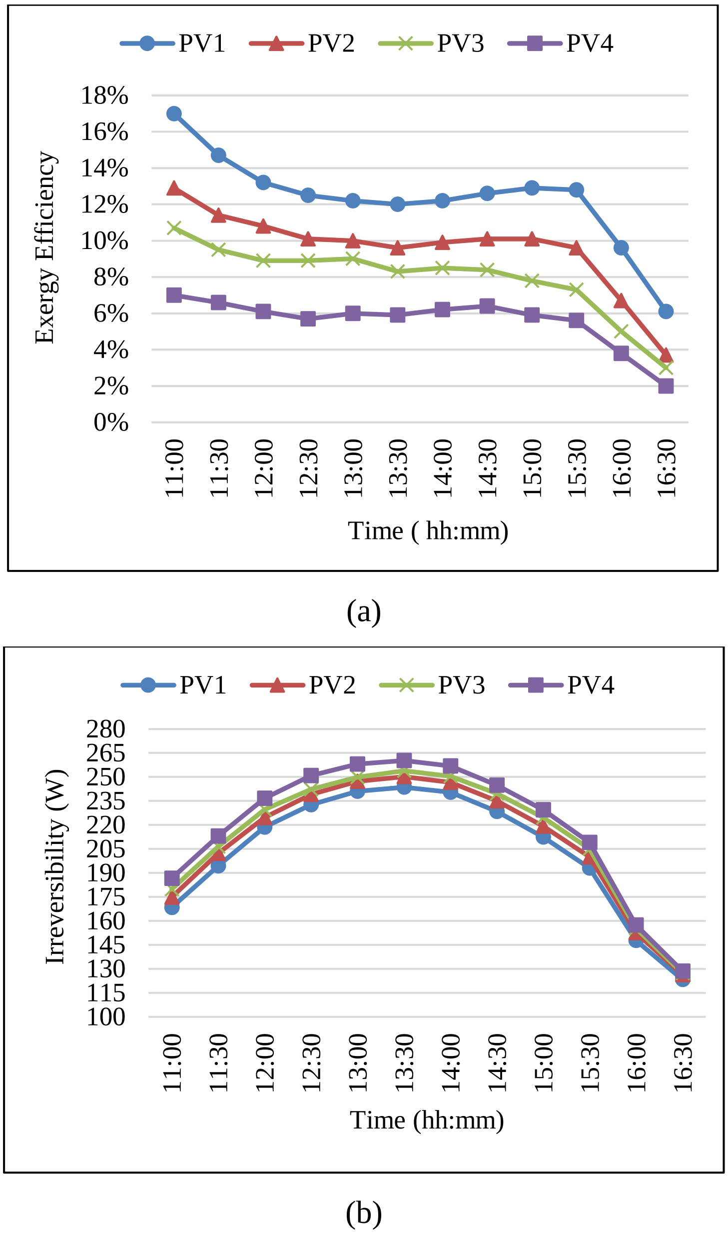


Figure 5. 7. (a): Exergy efficiency. (b): Irreversibility.

In Fig.5.7(a), we observe that the curve of the reference panel is higher than the other curves of the dusty panels. The average value of the exergy efficiency of the panels PV1, PV2, PV3 and PV4 is respectively 12.3%, 9.5%, 7.9% and 5.6%. From the curves in Fig.5.7(b), the irreversibility of the reference panel is lower than the irreversibility of panels PV2, PV3 and PV4. The effect of 109 µm thick dust particles on photovoltaic panels was analyzed in the next section.

5.2.THE EFFECT OF THE 109 µm THICK DUST PARTICLE ON THE ELECTRICAL AND THERMAL CHARACTERISTICS OF PV PANELS.

In this part, the effect of 109 µm thick dust particles on photovoltaic panels is examined and the results obtained have been analyzed. Figure 5.8 illustrates the evolution of solar radiation and ambient temperature as a function of time.

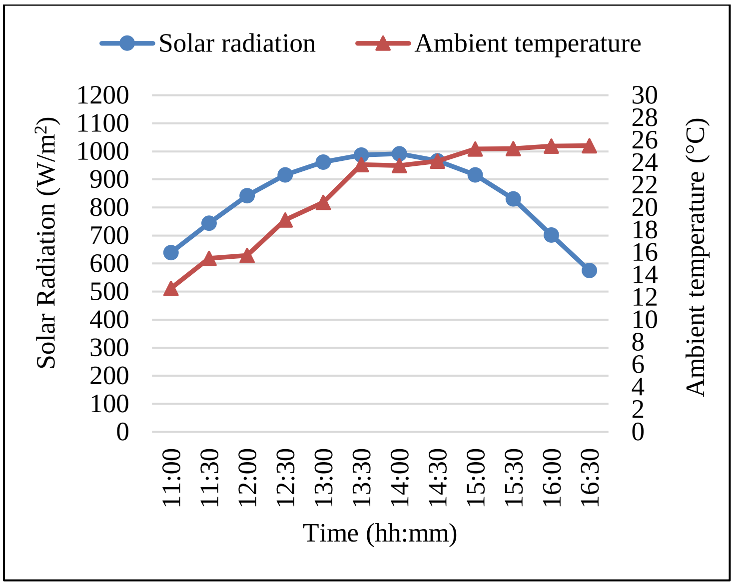


Figure 5. 8. Solar radiation and ambient temperature as a function of time.

It was found that the solar radiation increased from 639.67 W/m² to 991.67 W/m² between 11:00 and 14:00. And the ambient temperature varied from 12.80°C to 25.51°C between 11:00 and 16:30. In the course of the experiment, the calculated mean value of solar radiation and ambient temperature was 839.31 W/m² and 21.3°C. Figure 5.9 declares the change of back surface temperature of PV panels.

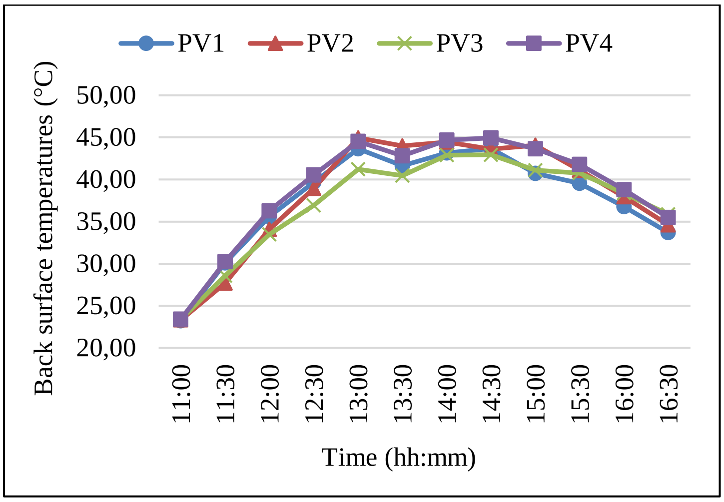
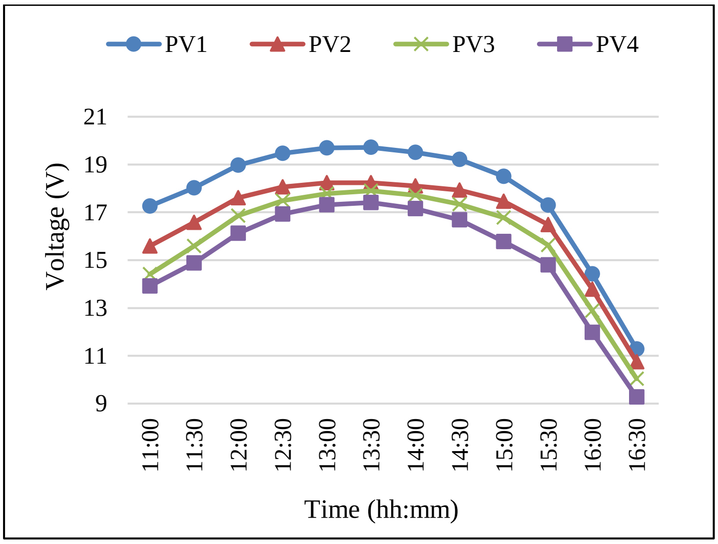
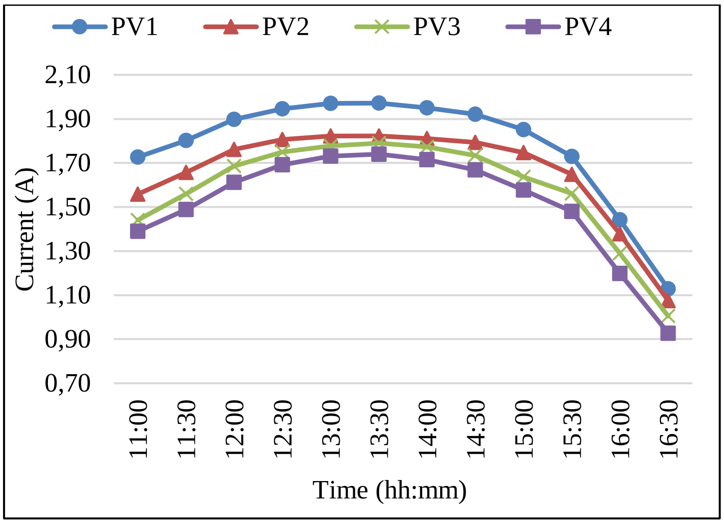


Figure 5. 9. The back surface temperatures of the panels.

At the start of the experiment, the back surface temperature values of the PV panels were 23.23°C, 23.33C, 23.36°C and 23.41°C. For the PV2 panel, the maximum temperature was at 13:00 with a value of 44.94°C. Whereas for panels PV1, PV3 and PV4, the values of the maximum rear surface temperature were 43.68°C, 42.94°C and 44.94°C at 14:30. The average temperature values of the rear surface of the photovoltaic panels were 37.62°C, 38.23°C, 37.16°C and 38.93°C. Figure 5.10(a, b) shows the impact of dust on the voltage and current of the PV panels studied.



(a)



(b)

Figure 5. 10. (a): Voltage variation curves. (b): Current variation curves.

As shown in Figure 5. 10(a, b), the voltage values of the four panels were respectively 17.26 V, 15.59 V, 14.41 V and 13.92 V at 11:00 and the current values of the panels were respectively 1.73 A, 1.56 A, 1.44 A and 1.39 A. And at 16:30, the voltage and current values of the panels were respectively 11.29 V, 10.75 V, 10.04 V, 9, 28 V, 1.13 A, 1.08 A, 1.0 A and 0.93 A. The voltage and current values of the photovoltaic panels reached their maximum values at 13:30. The average voltage values for the four photovoltaic panels were respectively 17.78 V, 16.57 V, 15.87 V and 15.19 V and the average current values were 1.78 A, 1.66 A, 1.58A and 1.52A. In Figure 5.11, we see the evolution of the power generated by the PV panels.

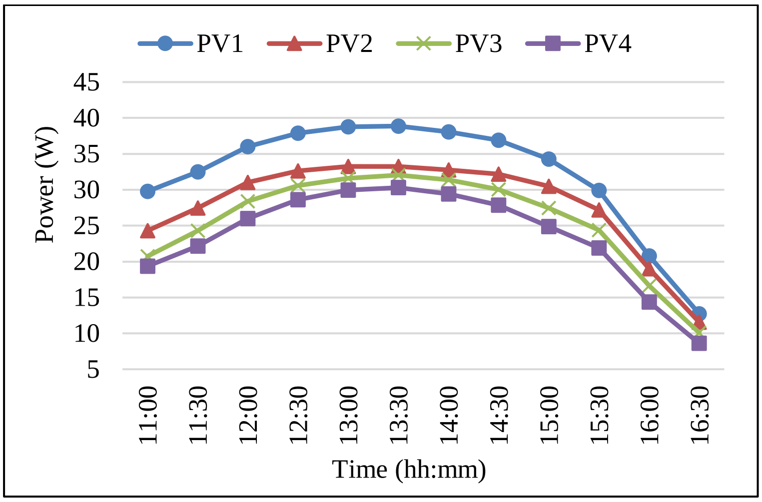


Figure 5. 11. Electric power variation curves.

According to the figure, the power values of the panels increase between 11:00 and 13:30, then start to decrease after 13:30. The maximum electrical powers recorded for the four PV panels were 38.87 W, 33.24 W, 32.04 W and 30.29 W. We also see that the curve of the PV1 panel is above the curves of the dusty panels (PV2, PV3 and PV4). Similarly, the curves of the PV2 and PV3 panels are above the curve of the PV4 panel. This means that the power values gradually decreased with increasing dust density on the surface of the PV panels. The average electrical powers of the four photovoltaic panels were 32.21 W, 27.92 W, 25.65 W and 23.62 W respectively. The electrical efficiency of the panels is shown in Figure 5.12.

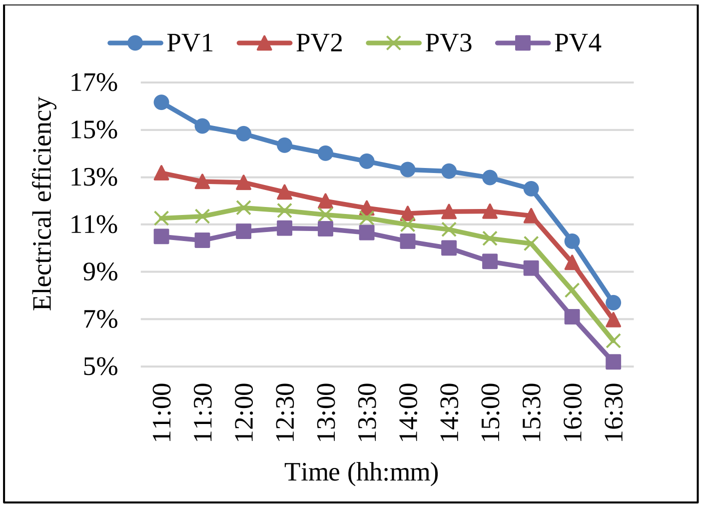


Figure 5. 12. Electrical efficiency of panels.

The average electrical efficiency of the panels was 13.2%, 11.5%, 10.5% and 9.6% respectively. The maximum efficiency values recorded for the photovoltaic panels during the experiment were 16.2%, 13.2%, 11.3% and 10.5% at the start of the experiment. While these values gradually decrease until they reach 7.7%, 7%, 6.1% and 5.1% respectively at 16:30. In Figure 5.13, the change of solar energy and solar exergy curve has been plotted.

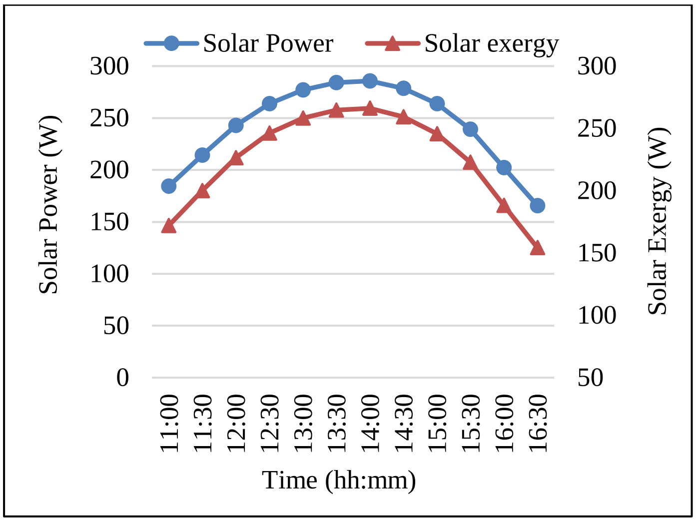
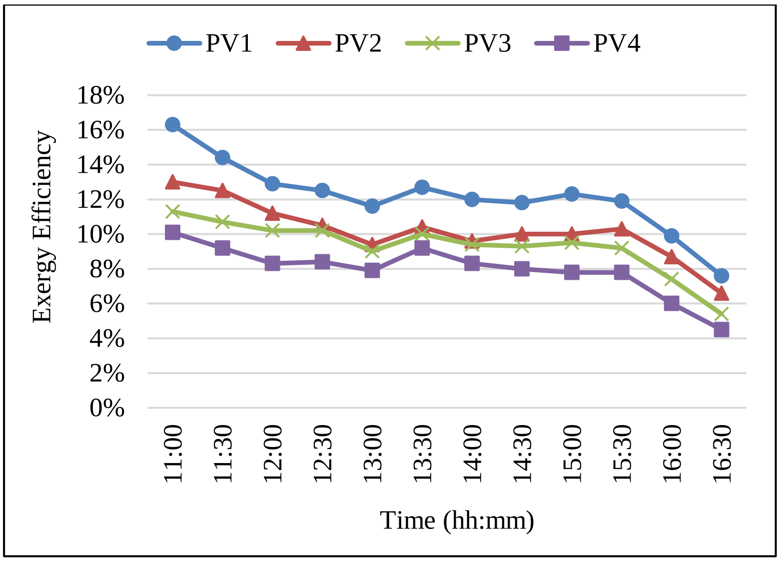
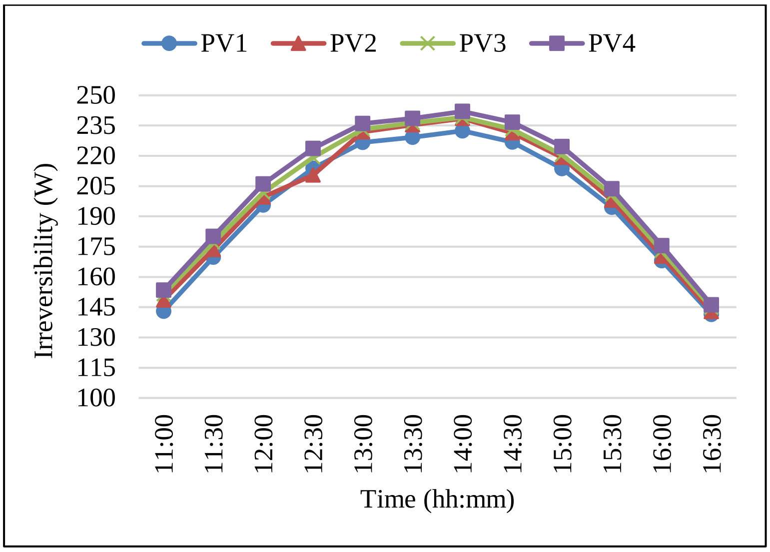


Figure 5. 13. Solar power and Solar exergy.

In Figure 5.13, it is observed that the maximum values of solar energy and solar exergy were 285.70 W and 266.12 W at 14:00. And the minimum solar energy and solar exergy values observed were 165.66 W and 154.24 W at 16:30. This shows us that the solar exergy curve is lower than the solar energy curve. The average value of solar energy and solar exergy was 240 W and 223 W. The exergy efficiency and the irreversibility of the panels PV are indicated in Figure 5.14(a, b).



(a)



(b)

Figure 5. 14. (a): Exergy efficiency. (b): Irreversibility.

From Figure 5.14(a), it can be seen that the maximum exergy efficiency for the four PV panels was 16.3%, 13%, 11.3% and 10.1%. The average values of the exergy efficiency of the PV panels are respectively 12.1%, 10.1%, 9.2% and 7.9%. From these average values, it can be seen that the PV1 panel has the highest exergy efficiency. Unlike the irreversibility curves in Figure 5.14(b), whose panel PV1 has the lowest irreversibility. The average values of the electrical characteristics (voltage, current, power and efficiency) of photovoltaic panels for dust particles of 61 μm and 109 μm are summarized in Table 5.1.

Table 5. 1. The average values of the electrical characteristics of photovoltaic panels for dust particles of 61 µm and 109 µm.

	Electrical characteristic	**61µm dust particle**	**109 µm dust particle**
PV1	Voltage (V)	17.81	17.78
	Current (A)	1.78	1.78
	Power (W)	32.79	32.21
	Electric efficiency (%)	12.8	13.2
PV2	Voltage (V)	16.00	16.57
	Current (A)	1.60	1.66
	Power (W)	26.70	27.92
	Electric efficiency (%)	10.3	11.5
PV3	Voltage (V)	14.75	15.87
	Current (A)	1.48	1.58
	Power (W)	22.84	25.65
	Electric efficiency (%)	8.7	10.5
PV4	Voltage (V)	13.07	15.19
	Current (A)	1.31	1.52
	Power (W)	17.95	23.62
	Electric efficiency (%)	6.8	9.6

From the data summarized in Table 5.1, the following interpretations can be drawn:

- For the dust deposition of 61 μm particles, the average power loss for the PV2, PV3 and PV4 panels compared to the PV1 panel is 18.57%, 30.34% and 45.26%. The average voltage losses of the panels with dust are observed at 10.16%, 17.18% and 26.6% compared to the PV1 panel, respectively. And the degradation of the average current of panels with dust was 10.11%, 16.85% and 26.40%. While the average efficiency reduction was 2.5%, 4.1%, and 6%, respectively.

- And for the dust deposition of 109 μm particles, the average power loss of the observed dusty panels was 13.31%, 20.36% and 26.66% compared to the reference panel. And the drop observed by the average voltage of the panels PV2, PV3 and PV4 was 6.80%, 10.74% and 14.56%, and that of the average current was 6.74%, 11.23% and 14 .60% respectively. The average electrical efficiency of the dusty panels was reduced by 1.7%, 2.7%, and 3.6% by reference to the PV1 panel.

PART 6
CONCLUSION

The fouling of dust particles on the surfaces of PV panels is very important in areas with high dust density (arid and semi-arid areas) and leads to major problems in their performance. Besides dust, other factors influence the performance of photovoltaic panels, such as temperature. The operation of photovoltaic panels can be affected by temperature because their electrical properties are very sensitive to temperature. But also, the decrease in solar radiation has a negative impact on the electrical performance of the PV panel. In this study, the impact of dust deposition on the electrical performance of photovoltaic panels was considered. The experimental results for 61 μm dust particles could be concluded as follows:

- The average electric power attenuation rate for the three PV panels (PV2, PV3 and PV4) compared to PV1 was 18.57%, 30.34% and 45.25%. The average electrical efficiency degradation was 2.5%, 4.1% and 6%. The decrease in exergy efficiency was 2.8%, 4.4%, 6.7%, respectively. The average temperature of the PV4 panel increased by 1.49°C compared to the PV1.

And for 109 μm dust particles:

- The average power of panels with dust is reduced by 13.31%, 20.36% and 26.66% and the average electrical efficiency attenuation is 1.7%, 2.7% and 3.6% respectively compared to the panel with reference. Exergy efficiency decreased 2%, 2,9%, and 4.2%, respectively. Similarly, the average temperature of the PV4 panel increases by 1.31°C compared to the average temperature of the PV1 panel.

- For solar radiation of 1039.83 W/m^2 and 493.71 W/m^2 and for a dust particle deposition of 61µm, the fouling rate of the average power of the PV4 panel was nearly 40% and 59.69% compared to the PV1. While for a solar radiation of 991.67 W/m^2 and 575 W/m^2 and for a dust particle deposit of 109µm, the average power of the PV4 panel was reduced by 22.70% and 32.49%.

From the above interpretations, it can be concluded that the density and size of dust particles on PV modules lead to a significant decrease in the power and efficiency of PV systems. It is confirmed that the smaller the size of the dust particles on the surface of the panels, the greater the degradation of the electrical performance of the panels. However, the study shows that the dust slightly increased the surface temperature of the photovoltaic panels. It is also observed that the electrical characteristics of dusty photovoltaic panels are less affected when the solar radiation is high than when it is low. It is therefore important to think about regular cleaning of the surfaces of the PV systems, to avoid a loss of performance of the PV panels and for more efficient electricity production.

PART 7
SUMMARY

In summary of this thesis, 61 μm dust particles significantly reduce the electrical characteristics of PV panels compared to 109 μm dust particles. Because small-size particles tend to deposit more easily on the surface of PV modules than large-size particles. After examination, it was found that the increase in the density of dust deposited on the PV panel can lead to the destruction of its electrical performance but also can cause a slight increase in the temperature of the rear face of the PV panels. The solar radiation falling on the surface of the PV panels is masked by the deposited dust particles, this is what leads to the reduction of the average power of the PV panel as well as the average electrical efficiency.

REFERENCES

1. Internet: Encyclopaedia Britannica, "Energy | Definition, Types, Examples, & Facts | Britannica", **https://www.britannica.com/science/energy** .
2. Mert Kaya, I., "Güneş Enerjisinin Atıksu Arıtma Tesislerinde Enerji Kaynağı Olarak Kullanılması", 126 (2016).
3. Koç, A., Yağlı, H., Koç, Y., and Uğurlu, İ., "Dünyada ve Türkiye ' de Enerji Görünümünün Genel Değerlendirilmesi General Evaluation of Energy Outlook in Turkey and the World", ***Mühendis Ve Makina Dergisi***, 59 (692): 84–112 (2018).
4. Aykar, C., "Türkiye Ege Bölgesi Güneş Enerjisi Potansiyeli Tekno-Ekonomik Analizi", ***Kütahya Dumlupınar Üniversitesi Lisansüstü Eğitim Öğretim ve Sınav Yönetmeliği***, (2016).
5. Torunoğlu Gedık, Ö., "Türkiye'de Yenilenebilir Enerji Kaynakları Ve Çevresel Etkileri_", ***Istanbul Teknik Üniversitesi Fen Bilimleri Enstitüsü***, (2015).
6. Tsoutsos, T., Frantzeskaki, N., and Gekas, V., "Environmental impacts from the solar energy technologies", ***Energy Policy***, 33 (3): 289–296 (2005).
7. Düzenli, A., "Güne Enerjili Su Pompalam Sistemleri", ***Istanbul Teknik Üniversitesi Fen Bilimleri Enstitüsü***, (2010).
8. Ceylan, İlhan;Gürel, E., "Güneş Enerjisi Sistemleri ve Tasarımı", ***Dora Yayıncılık***, Bursa, 1–261 (2018).
9. Kabir, E., Kumar, P., Kumar, S., Adelodun, A. A., and Kim, K. H., "Solar energy: Potential and future prospects", ***Renewable And Sustainable Energy Reviews***, 82 (August 2017): 894–900 (2018).
10. Cihan, E., "YENİLENEBİLİR ENERJİ VE TÜRKİYE'DE GÜNEŞ ENERJİSİ", ***Hasan Kalyoncu Üniversitesi Sosyal Bilimler Enstitüsü***, (2019).
11. Internet: Iceland Data, "Climate and Temperature Development in Iceland", **https://www.worlddata.info/europe/germany/climate.php%0Ahttps://www.worlddata.info/europe/iceland/climate.php** .
12. Internet: Karafil, A., "Solar-Energy-Map-of-Turkey-26", **https://www.researchgate.net/figure/Solar-Energy-Map-of-Turkey-**

26_fig3_337307247 .

13. Özek, E., "Peyzaj Mimarisi Uygulamalarında Güneş Enerjisinin Kullanımının Değerlendirmesine Yönlik Bir Araştırma Ve Yalova- Termal Yolu Örneği", ***Istanbul Teknik Üniversitesi Fen Bilimleri Enstitüsü***, (2009).
14. Küçükilhan, G., "Fotovoltaık Güç Sistemlerinin Modellenmesi Ve Şebekeye Etkilerinin İncelenmesi", ***Afyon Kocatepe Üniversitesi Fen Bilimleri Enstitüsü***, (2017).
15. Internet: Bellis, M., "The History and Definition of Solar Cells", **https://www.thoughtco.com/history-of-solar-cells-1992435** .
16. Öztürk, H. H., "Güne Enerjisinden Fotovoltaik Yöntemle Elektri Üretiminde Güç Dönüşü Verimi Ve Etkili Etmenler", (2004).
17. Internet: Sarkar, S., "Working Principle of PV Device | Download Scientific Diagram", **https://www.researchgate.net/figure/Working-Principle-of-PV-Device_fig8_334697623** .
18. Urrutia, L. Z., "Measurements and simulations of the performance of the PV systems at the University of Gävle Measurements and simulations of the performance of the PV systems at the University of Gävle", ***Unıversity of Gavle***.
19. Internet: Kumar, T., "Explain the Construction and Working of Solar Cell", **https://www.sarthaks.com/1392412/explain-the-construction-and-working-of-solar-cell** .
20. Internet: Roderick, A., "Understanding the Composition of a Solar Cell - Technical Articles", **https://eepower.com/technical-articles/understanding-the-composition-of-a-solar-cell/#** .
21. ÇELİK, A. and CELIK, A. N., "Polikristal Tür bir Fotovoltaik Panelin I-V Karakteristiğinin Analitik Modellenmesi ve Deneysel Validasyonu", ***Düzce Üniversitesi Bilim Ve Teknoloji Dergisi***, 8: 2491–2515 (2020).
22. Ghania, A., "Study Of Silicon Solar Cells Performances Using The Impurity Photovoltaic Effect", ***Université Ferhat Abbas–Setif***, (2012).
23. Internet: David Darling, "I-V Curve (of a Photovoltaic Device)", **http://www.daviddarling.info/encyclopedia/I/AE_I-V_curve.html** .
24. Internet: Svarc, J., "Solar Panel Construction — Clean Energy Reviews", **https://www.cleanenergyreviews.info/blog/solar-panel-components-construction** .

25. Akdere, R., "Kismi gölgelenme koşullarindaki fv sistemlerin maksimum güç noktasinin derin öğrenme yöntemiyle tahmini", ***Kahramanmaraş Sütçü İmam Üniversitesi Fen Bilimleri Enstitüsü***, (2022).
26. Internet: Renewable Energy Hub, "What Is the Difference Between Monocrystalline and Polycrystalline Solar Panels? - The Renewable Energy Hub", **https://www.renewableenergyhub.co.uk/main/solar-panels/what-is-the-difference-between-monocrystalline-and-polycrystalline-solar-panels**.
27. Internet: Mofiz, A., "Amorphous Silicon PV Modules Opens-up New Possibilities for Solar Power Generation", **https://www.jakson.com/blog/amorphous-silicon-pv-modules-opens-up-new-possibilities-for-solar-power-generation/** .
28. Meral, M. E. and Diner, F., "A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems", ***Renewable and Sustainable Energy Reviews***, 15 (5): 2176–2184 (2011).
29. Internet: LEONICS, "Basics of Solar Cell, Solar Photovoltaic Modules", **http://www.leonics.com/support/article2_13j/articles2_13j_en.php** .
30. Fouad, M. M., Shihata, L. A., and Morgan, E. S. I., "An integrated review of factors influencing the performance of photovoltaic panels", ***Renewable And Sustainable Energy Reviews***, 80 (June): 1499–1511 (2017).
31. Lasfar, S., Haidara, F., Mayouf, C., Abdellahi, F. M., Elghorba, M., Wahid, A., and Kane, C. S. E., "Study of the influence of dust deposits on photovoltaic solar panels: Case of Nouakchott", ***Energy For Sustainable Development***, 63: 7–15 (2021).
32. Tripathi, A. K., Murthy, C. S. N., and Aruna, M., "Experimental Investigation of Dust Effect on PV Module Performance", ***Global Journal of Researches In Engineering: J General Engineering***, 17 (November): 35–39 (2017).
33. Ketjoy, N. and Konyu, M., "Study of dust effect on photovoltaic module for photovoltaic power plant", ***Energy Procedia***, 52: 431–437 (2014).
34. Rao, A., Pillai, R., Mani, M., and Ramamurthy, P., "Influence of dust deposition on photovoltaic panel performance", ***Energy Procedia***, 54: 690–700 (2014).
35. Gholami, A., Khazaee, I., Eslami, S., Zandi, M., and Akrami, E., "Experimental investigation of dust deposition effects on photo-voltaic output performance", ***Solar Energy***, 159 (November 2017): 346–352 (2018).

36. Katoch, M., Kumar, K., and Dahiya, V., "Dust accumulation and reduction in electrical performance of solar PV panels", ***Materials Today: Proceedings***, 46: 6608–6612 (2020).
37. Al-hasan, A. Y. and Ghoneim, A. A., "A new correlation between photovoltaic panel’s efficiency and amount of sand dust accumulated on their surface", ***International Journal of Sustainable Energy***, 24 (4): 187–197 (2005).
38. Khodakaram-Tafti, A. and Yaghoubi, M., "Experimental study on the effect of dust deposition on photovoltaic performance at various tilts in semi-arid environment", ***Sustainable Energy Technologies and Assessments***, 42 (January): 100822 (2020).
39. Abderrezek, M. and Fathi, M., "Experimental study of the dust effect on photovoltaic panels’ energy yield", ***Solar Energy***, 142: 308–320 (2017).
40. Chen, Y., Liu, Y., Tian, Z., Dong, Y., Zhou, Y., Wang, X., and Wang, D., "Experimental study on the effect of dust deposition on photovoltaic panels", (2019).
41. Said, S. A. M. and Walwil, H. M., "Fundamental studies on dust fouling effects on PV module performance", ***Solar Energy***, 107: 328–337 (2014).
42. Dida, M., Boughali, S., Bechki, D., and Bouguettaia, H., "Output power loss of crystalline silicon photovoltaic modules due to dust accumulation in Saharan environment", ***Renewable and Sustainable Energy Reviews***, 124 (January 2019): 109787 (2020).
43. Juaidi, A., Haj, H., Abdallah, R., Abdalhaq, R., and Albatayneh, A., "Experimental validation of dust impact on-grid connected PV system performance in Palestine : An energy nexus perspective", ***Energy Nexus***, 6 (April): 100082 (2022).
44. Dhaouadi, R., Al-Othman, A., Aidan, A. A., Tawalbeh, M., and Zannerni, R., "A characterization study for the properties of dust particles collected on photovoltaic (PV) panels in Sharjah, United Arab Emirates", ***Renewable Energy***, 171: 133–140 (2021).
45. Kadhum, J. A., Rida, K. S., Al-waeli, A. A., and Al-Asadi, K. A., "The Impact of Dust Accumulation on the PV Panels Outcomes", ***International Journal Of Computation And Applied Sciences***, 1 (3): 11–14 (2016).
46. Sulaiman, S. A., Singh, A. K., Mokhtar, M. M. M., and Bou-Rabee, M. A.,

"Influence of dirt accumulation on performance of PV panels", ***Energy Procedia***, 50: 50–56 (2014).

47. Mejia, F., Kleissl, J., and Bosch, J. L., "The effect of dust on solar photovoltaic systems", ***Energy Procedia***, 49: 2370–2376 (2014).
48. Ali Sadat, S., Faraji, J., Nazififard, M., and Ketabi, A., "The experimental analysis of dust deposition effect on solar photovoltaic panels in Iran's desert environment", ***Sustainable Energy Technologies and Assessments***, 47 (August): 101542 (2021).
49. Saidan, M., Albaali, A. G., Alasis, E., and Kaldellis, J. K., "Experimental study on the effect of dust deposition on solar photovoltaic panels in desert environment", ***Renewable Energy***, 92: 499–505 (2016).
50. Rahman, M. M., Islam, M. A., Karim, A. H. M. Z., and Ronee, A. H., "Effects of Natural Dust on the Performance of PV Panels in Bangladesh", ***International Journal of Modern Education and Computer Science***, 4 (10): 26–32 (2012).
51. Chen, J., Pan, G., Ouyang, J., Ma, J., Fu, L., and Zhang, L., "Study on impacts of dust accumulation and rainfall on PV power reduction in East China", ***Energy***, 194: 116915 (2020).
52. Hussain, A., Batra, A., and Pachauri, R., "An experimental study on effect of dust on power loss in solar photovoltaic module", ***Renewables: Wind, Water, and Solar***, 4 (1): (2017).
53. Nipu, N. N., Saha, A., and Khan, F., "Effect of accumulated dust on the performance of solar PV module", ***International Journal of Engineering And Technology(UAE)***, 6 (1): 9–12 (2017).
54. Abass, K. I., M Al-Zubaidi, D. S., and K Al-Waeli, A. A., "Effect of pollution and dust on PV performance", ***International Journal of Civil, Mechanical And Energy Science (IJCMES)***, 3 (4): 181–185 (2017).
55. Oral, M., "Solar Energy Potential of Turkey and Evaluation of Pv 1 Applications in Local Scale :Case of Karabük Province", ***International Journal of Geography and Geography Education (IGGE)***, 42: 482–503 (2020).
56. Internet: Tabak, A., "Solar-Energy-Potential-of-Karabuek-Province_fig1_355042240", **https://www.researchgate.net/figure/Solar-Energy-Potential-of-Karabuek-Province_fig1_355042240** .

RESUME

Azıza IDRISS WARSAMA obtained her baccalaureate in 2016. Graduated from the Faculty of Sciences of the University of Djibouti in 2019. Pursuing graduate studies in progress at the Department of Energy Systems Engineering.