EXPERIMENTAL INVESTIGATION OF FORCED AIR COOLED PV/T COLLECTORS PERFORMANCE SUPPORTED BY PHASE CHANGE MATERIAL AND FINNED STRUCTURE

Ahmad AL HARIRI

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Thesis Advisor
Assist. Prof. Dr. Selcuk SELIMLI

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Ahmad AL HARIRI

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

Thesis Advisor
Assist. Prof. Dr. Selcuk SELIMLI

KARABUK
May 2022

I certify that in my opinion the thesis submitted by Ahmad AL HARIRI titled "EXPERIMENTAL INVESTIGATION OF FORCED AIR COOLED PV/T COLLECTORS PERFORMANCE SUPPORTED BY PHASE CHANGE MATERIAL AND FINNED STRUCTURE" is fully adequate in scope and in quality as a thesis for the degree of Master of Science.

Assist. Prof. Dr. Selcuk SELIMLI ....

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. May 12, 2022

Examining Committee Members (Institutions)		Signature
Chairman	: Prof. Dr. Kurtuluş BORAN (GU)	....
Member	: Assist. Prof. Dr. Mehmet OZKAYMAK (KBU)	....
Member	: Assist. Prof. Dr. Selcuk SELIMLI (KBU)	....

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Ahmad AL HARIRI

ABSTRACT

M. Sc. Thesis

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Ahmad AL HARIRI

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

Thesis Advisor:
Assist. Prof. Dr. Selcuk SELIMLI

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In this experimental study, the active cooling process was applied with a fan powered air flow and supported with PCM mixture that is paraffin and steel foam. The mixture was filled in the modules' back surface and enclosed with an inclined and flat finned heat sink. The air flow was created between the heat sink fins to provide forced convective cooling with the fan. The inclined and flat fin heat sink is called PV/T1 and PV/T2. The reference module was named PV and used for comparison. The back surface temperatures, thermal and electrical powers, and efficiencies were evaluated and compared with PV module data. Resultantly, PV/T1 and PV/T2 collectors were cooled by 12.29% and 21.97% more relative to PV module. The electrical efficiency for each of PV/T1 and PV/T2 was 5.12 % and 6.08%, while for the PV module it was 4.37%. The overall efficiencies for the PV/T1 and PV/T2 collectors were 43.74% and 62.3%. Exergy efficiencies values were 4.68% for PV module, 5.65% and 6.8% for PV/T1 and PV/T2 collectors.

Key Words **:** PCM mixture, active cooling, PV/T collector, energy, and exergy efficiency, solar energy.

Science Code : 91441

ÖZET

Yüksek Lisans Tezi

FAZ DEĞİŞTİREN MALZEME VE KANATLI YAPI İLE DESTEKLENEN CEBRİ HAVA SOĞUTMALI PV/T KOLLEKTÖRLERİNİN PERFORMANSININ DENEYSEL İNCELENMESİ

Ahmad AL HARIRI

Karabük Üniversitesi
Lisansüstü Eğitim Enstitüsü
Enerji Sistemleri Mühendisliği Anabilim Dalı

Tez Danışmanı:
Dr. Öğr. Üyesi Selçuk SELİMLİ
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Bu deneysel çalışmada, fan destekli hava akımı ile aktif soğutma işlemi uygulanmış ve parafin ve çelik köpük olan PCM karışımı ile desteklenmiştir. Karışım, modüllerin arka yüzeyine doldurulmuş ve eğimli ve düz kanatlı bir ısı alıcı ile kapatılmıştır. Fan ile cebri konvektif soğutma sağlamak için ısı emici kanatçıklar arasında hava akışı oluşturulmuştur. Eğimli ve düz kanatlı soğutucuya PV/T1 ve PV/T2 adı verilir. Referans modülü PV olarak adlandırıldı ve karşılaştırma için kullanıldı. Arka yüzey sıcaklıkları, termal ve elektriksel güçler ve verimlilikler değerlendirildi ve PV modül verileriyle karşılaştırıldı. Sonuç olarak, PV/T1 ve PV/T2 kollektörleri, PV modülüne göre %12,29 ve %21,97 daha fazla soğutulmuştur. PV/T1 ve PV/T2'nin her biri için elektrik verimliliği %5,12 ve %6,08 iken, PV modülü için %4,37 idi. PV/T1 ve PV/T2 kollektörler için genel verimlilikler %43,74 ve %62,3 idi. Ekserji verim değerleri PV modülü için %4,68, PV/T1 ve PV/T2 kollektörleri için %5,65 ve %6,8'dir.

Anahtar Kelimeler : PCM karışımı, aktif soğutma, PV/T kolektör, enerji ve ekserji verimliliği, güneş enerjisi.

Bilim Kodu **:** 91441

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Dedicated to my dear parents.

To my dear wife, who shared me patience and hardship. To my children ,my hope in this life. To all who have left a beautiful imprint on us.

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SYMBOLS AND ABBREVIATIONS

SYMBOLS

A_m : Module surface area.

α : Absorptivity of a cell.

β_o : Thermal coefficient of electrical efficiency.

$C_{p,air}$: Air specific heat.

$\Delta\dot{E}$: Energy difference.

$\Delta\dot{E}x$: Exergy difference.

$\dot{E}_{elec}$: Electrical energy.

$\dot{E}_{in}$: Inlet energy.

$\dot{E}_{loss}$: Lost heat energy.

$\dot{E}_{out}$: Outlet energy.

$\dot{E}_{solar}$: Solar power.

$\dot{E}_{th}$: Heat remove rate.

η_c : Cell efficiency.

η_{elec} : Electrical efficiency.

η_{ex} : Exergy efficiency.

η_o : Overall efficiency.

η_{th} : Thermal efficiency.

$\dot{E}x_{air}$: Air exergy.

$\dot{E}x_{dest}$: Destroyed exergy.

$\dot{E}x_{elec}$: Electrical exergy.

$\dot{E}x_{in}$: Inlet exergy.

$\dot{E}x_{out}$: Outlet exergy.

$\dot{E}x_{solar}$: Solar exergy.

$\dot{E}x_{th}$: Thermal exergy.

FF : Fill factor.

G : Solar radiation.

G_o : STC Solar radiation.

I_m : Maximum power current.

$\dot{m}_{air}$: Air mass flow rate.

PF : Packing factor.

P_{max} : Maximum power.

τ : Transparency.

T_a : Ambient temperature.

T_c : Cell temperature.

T_s : Surface temperature.

V_m : Maximum power voltage.

ABBREVITIONS

$NOCT$: Nominal operating cell temperature.

PV : Photovoltaic module.

PV/T : Photovoltaic/thermal collector.

STC : Standard test conditions.

PART 1

INTRODUCTION

The increase in population growth and the enhancement of technology and economic are accompanied by an increase in needed energy, which is mainly come across using fossil fuels, which are produced from remnants of living plants and animals across millions of years [1]. Burning fossil fuel produces carbon dioxide, which is the main problem for fossil fuels because carbon dioxide is a major partner in global warming (GHG). The fossil fuels are categorized as non-renewable energy resources, which means that they can either be expired or drained out [2]. Alternative energy resources have been discovered and merged to generate energy and are called renewable energy. Wind, solar, geothermal energy, tides, hydropower, and bioenergy cover these sources. It is most welcome because it will not be exhausted, and it produces lower emissions (GHG). It is a target for many countries and has become a necessity for the world and the environment because it is clean, environmentally friendly, harmless, and sustainable. According to the 2017 REN21 Report, in 2016, 10.4% of the total consumed energy was from modern renewable energy, while fossil fuels constitute around 79.5%, and solar energy technology occupied the highest installation capacity in for 2017, Figure 1.1 [3]. Based the study carried on by the World Energy Alliance for the last few years, it was concluded that [4]:

- Electricity demand will double by 2060.
- The requirement of clean energy will request big growth in infrastructure and Development of delivery service systems to consumer.
- It is expected that fossil fuel's share in fundamental energy will be reduced to 50–70% of the existing 80%, with the advanced technologies for producing electricity from renewable resources. New opportunities will be created from producing energy from renewable resources, and a lot of challenges will appear for new systems.

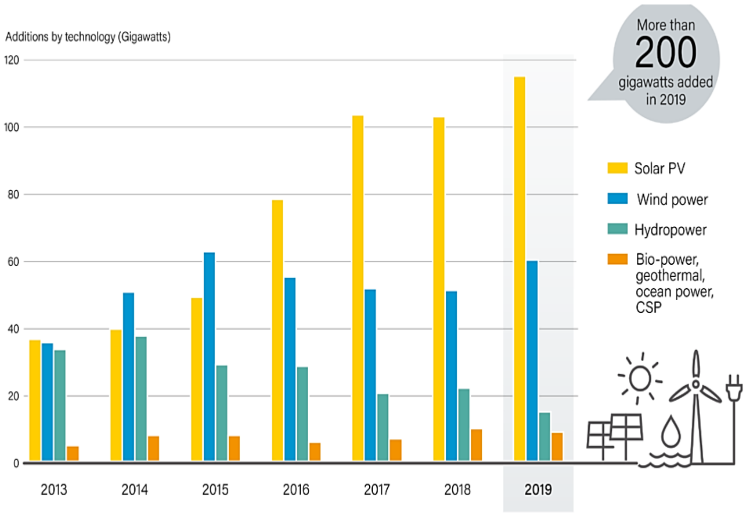

Figure 1.1. Yearly addition of renewable energy capacity 2013-2019 [3].

1.1. OVERVIEW OF RENEWABLE ENERGIES

On our planet, there are various inexhaustible and constantly renewed formats of renewable energies: wind, sunlight, biomass, water, and heat under the earth. Their advantage appears when renewable energy sources emit lower carbon parallel to traditional fuels. Various forms of renewable sources are exemplified in Figure 1.2 [4].

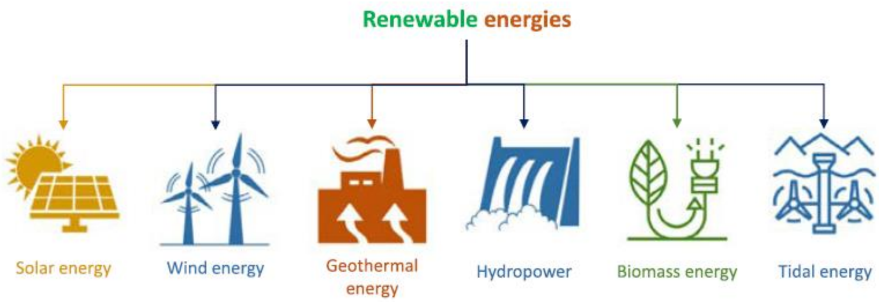

Figure 1.2. Renewable energies [4].

Hydropower: an energy production technology where dams are used to pass the trapped water behind them onto the turbines to spin it in order to produce electricity. There are a lot of small installed stations on rivers or aqueducts to convert water kinetic energy to electrical energy. The water is lifted to the upper tanks, where this process is considered energy storage and is converted into electrical energy when used to power the turbines [4]. Biomass is an organic substance that uses photosynthesis processes to convert the sunlight to chemical energy that produces heat by burning it. There are many examples of bioproducts such as timber, food waste, agricultural crops, animal dung, domestic waste and wastewater, which are subject to the process of decomposition within bioreactors to produce fuel or biogas. Thermal energy produced from these biomaterials is typically used for residential accommodation, cooking, and water heating or more broadly for industrial thermal processes [5]. Wind power is a form of the kinetic energy of the wind. Electrical energy can be generated from energy carried by wind by power conversion machines or used directly in water pumping, sailing ships or milling, and it is a renewable resource that is considered clean, useable, and close at hand type of energy to create electricity. This technology is free of pollutants. The kinetic energy of the wind is converted by a wind turbine to power electric generators for the purposes of generating electrical energy [6]. Wind electricity production increased significantly between 2009 and 2013, and in 2016 the electricity produced from wind energy was 16% of the electricity generated from renewable energy sources [7]. Geothermal energy is thermal energy that comes from earth's depth. water or other liquids are used to grab the internal heat energy of the earth, located in reservoirs at a depth of between 300 and 8000 meters in the ground. This kind of energy can be used directly for heating purposes, and power plants use this type of energy have low emissions [8]. In the last years, direct usage of geothermal power has raised by 8%. This energy can only be carried out from a few locations, although it is available all the time. A few countries including Kenya, Indonesia and Turkey have recently installed geothermal power plants [9]. Tidal force is one form of energy within the oceans that benefits from the iterated rising and falling water levels to generate electric power. This energy is harnessed to run turbines and generators using the mechanical power of the tides. Though sea and ocean thermal power plants are in their beginnings, systems for using tidal and wave energy capacity are on the rise, reached 532 MW in 2018 [4]. The solar energy is the related subject of this study and given more detailed information under the new title with more details.

1.2. ENERGY IN TURKEY

Turkey ranks 37th among the world's countries in terms of land area, with an area of 783,562 square kilometers, a population of 83 million in 2020, and geographically located between the continents of Asia and Europe [10].

In 2021, electric energy consumption in Turkey was 7.7% greater compared to 329.6 billion kWh in the previous year, while electricity production increased by 8.1% compared with the previous year, and the produced electricity reached 331.5 billion kWh, an increase of 8.1% compared to the previous year. At the end of March 2022, Turkey's installed capacity reached 100,334 megawatts broken down by resource; 25.4% natural gas, 20.4% coal, 31.4% hydraulic, 10.8% wind, 8.0% solar, 1.7% geothermal and 2.4% from other sources. The number of electric power plants in Turkey also increased to 10,631: 747 hydroelectric plants, 67 coal, 355 wind, 63 geothermal, 348 natural gas, 8,566 solar, and 485 other sources [11].

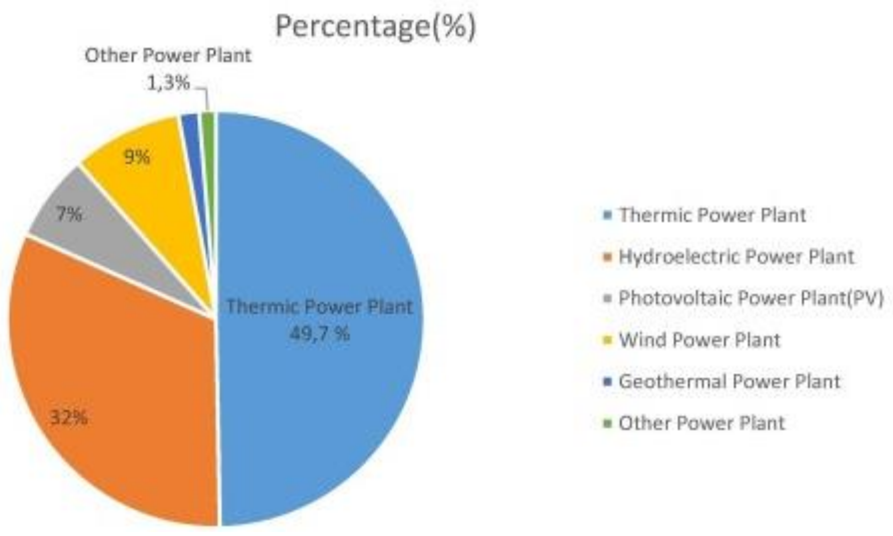

figure 1.3. Turkey's ratio installed power according to resources (2020) [12].

1.3. SOLAR ENERGY POTENTIAL IN TURKEY

Because of the geographical position that Turkey possesses, it has great potential for solar energy, where the average annual solar radiation period is estimated at 2741 hours per year, the average daily radiation period is 7.5 hours per day, and the solar radiation is estimated at 1527.46 kWh/m² annually and 4.18 kWh/m² daily. The rate of solar brightness in the southern and eastern parts is higher than in the western and northern parts. The highest levels of radiation are in the months of June and July, and the lowest level is in the months of December and January. This state is shown in the Atlas of solar energy potential [12].

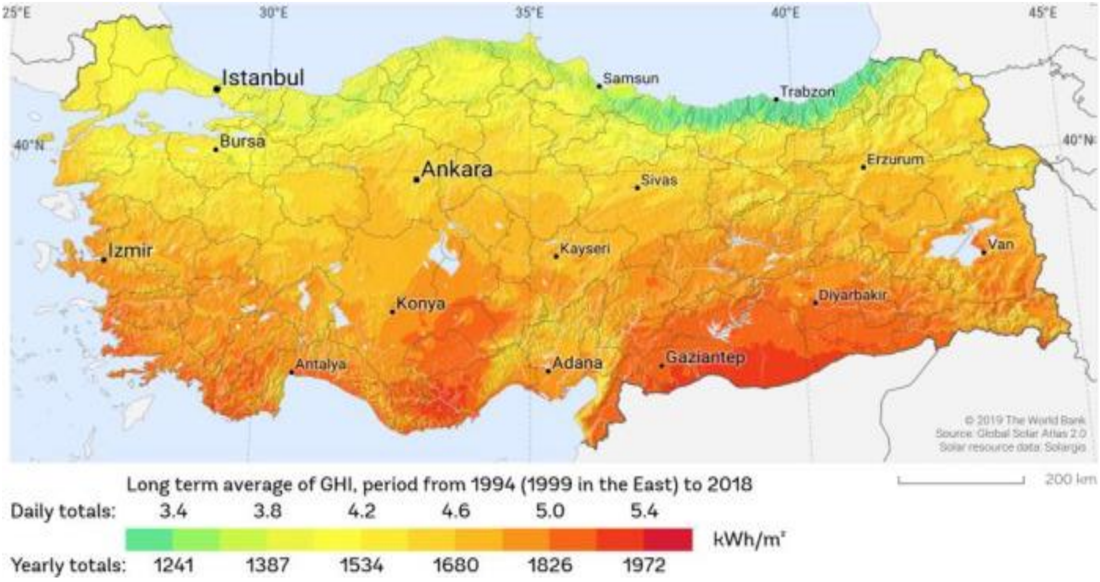

Figure 1.4. Solar energy potential atlas in Turkey[12].

As for the expectant growth rate of solar electric capacity in Turkey, according to modeling studies, by 2030, 14% of the electrical capacity will be from solar electric and this percentage will reach 29% by 2040. This means that electricity production from solar energy will be 17 GW by 2030 and 40 GW by 2040. This rise in installed PV capacity between 2030 and 2040 will represent 70% of the whole energy that will be installed in this period. 6 GW of the 40 GW that will be installed until 2040, will be roof top installations, and the rest will be photovoltaic power stations [13].

1.4. SOLAR ENERGY SOURCE

The sun is a very hot gas sphere on average. It is on average 1.5×10^{11} m far from our planet, with an estimated diameter of 1.39×10^{9} m. Sun has the effect of a black body its surface temperature is 5777 K, and it’s responsible for almost all life on earth and most forms of renewable energy on the surface of earth. The energy in the sun is produced from the fusion reactions that occur inside it, and the most important process is the process of fusing hydrogen (four protons) to form helium (one helium nucleus) where the energy produced from the difference between the mass of the helium nucleus and the mass of the four protons is transformed into Energy at very high temperatures, this energy is transferred to the surface and then send out to space [14,15]. Depending on well-established estimations, average intensity of solar energy radiation only the outside of the earth's atmosphere is 1366 W/m^2, Figure 2.1**,** usually called the solar constant, and the estimated total power reached earth from solar irradiation is about 1.73×10^{17} W. On average, there are 365 days a year, and 86400 s a day. The yearly total energy reaching earth from solar radiance is:

$365 \times 86400 \times 1.73 \times 10^{17} \cong 5.46 \times 10^{24}$ J [14].

The arriving of solar imposed power is schematised in Figure 1.3.

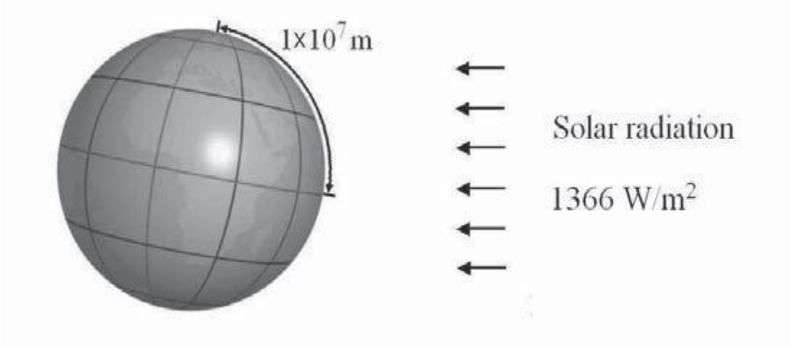

Figure 1.5. The yearly solar energy that reaches earth's surface [14].

To get an idea about this energy amount how much is it, we will compare it to the yearly consumed energy; see Figure 1.4. In the years between 2005 and 2010, the yearly consumption of energy in the world was estimated as 500 EJ. The world's energy requirement can be met just by 1% of the annual solar energy reaching the earth [14,16].

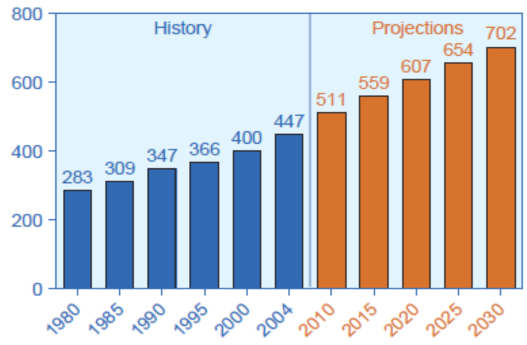

Figure 1.6. Consumpted energy in the world, 1980–2030 [17].

1.5. THE SUN RADIATION

When sunlight goes into the atmosphere, some is absorbed or scattered, and some passes in the atmosphere and is either reflected or absorbed by physical objects on the ground, so not all the sun's radiation can cross to the earth's surface, up to 30% of the radiation reflected by the atmosphere, and 20% of the solar radiation is trapped in the atmosphere and clouds. The reaching radiation to earth passing through the atmosphere is about 50% only. Sunlight that reaches earth without scattering is called beam or direct radiation; scattered sunlight is named diffuse radiation. The reflected radiation from the ground is called albedo. Global radiation is the sum of these components [18,19]. The amount of solar radiation energy, fallen on the earth surface depends on the location of that surface, the horizontal incline angle of the surface, the surface orientation, time of year, weather conditions, the area of the receiving surface, the reception surface characteristics and irradiation time [18]. Solar radiational components are shown in Figure 1.5.

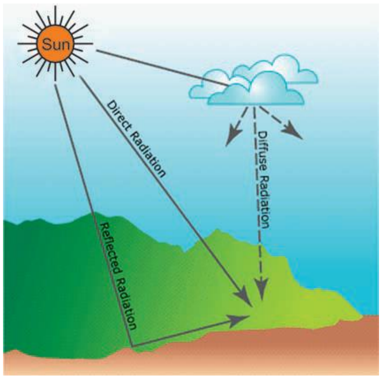

Figure 1.7. Beam, diffuse, and reflected radiation [19].

PART 2

SOLAR ENERGY SYSTEMS

After sunlight reaches the earth, it can be converted into chemical energy through plants, thermal energy through devices called solar collectors, or electrical energy through photovoltaic units as seen in Figure 2.1 [20].

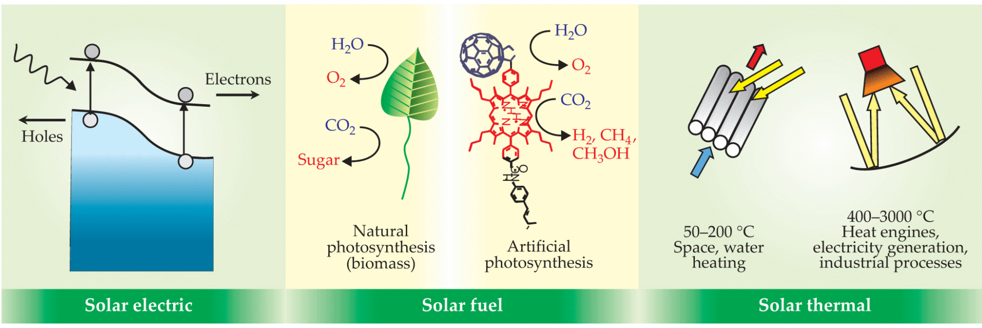

Figure 2.1. Conversion of solar energy [20].

2.1. PV SYSTEMS AND APPLICATIONS

In general, we can categorize Photovoltaic systems into PV/T and PV. It is possible to divide the fields of application of solar energy into two main groups active and passive. In the passive application of solar energy, solar power is utilized without using special equipment. This method of usage is also called indirect solar energy usage [21]. In terms of electrical applications, they are classified into grid-connected and stand-alone systems. The solar energy yield in stand-alone systems is Associated to the need for energy. Because the output of solar energy a lot of times does not synchronize with the ordered energy for loads, extra equipment such as batteries is generally used for storage purposes. When additional power resource supports the system, such as a generator or wind turbine in this case the system is called a hybrid system. In systems directly connected to the grid, the public electricity network acts as storage for energy [18]. PV system configurations for different applications can be sorted as:

- Stand-alone PV systems without storage battery.and with storage battery.
- On-Grid interactive PV system.
- Hybrid systems.
- Building Integrated PV systems.

The application examples of PV systems are given in Figure 2.2.

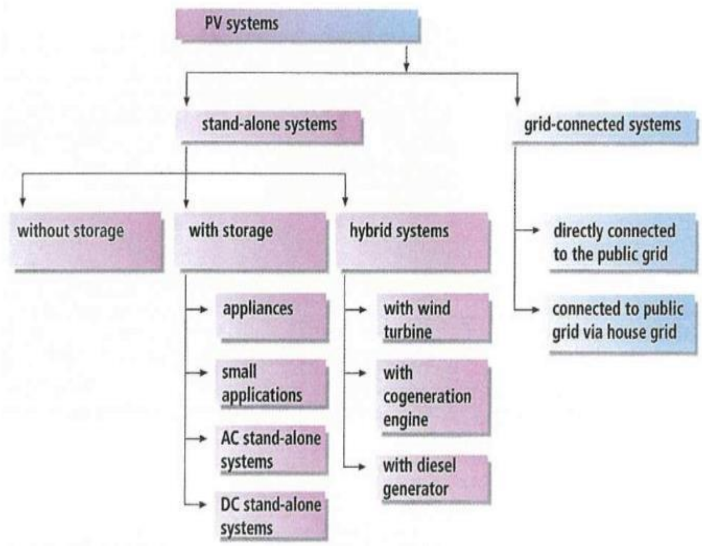

Figure 2.2. Types of PV systems [22].

2.1.1. Stand- Alone PV Systems Without Storage Battery

Stand alone applications of solar energy are used in systems intended for the purpose of operating in a specific period, which can be implemented in the period of availability of solar radiation like water pumps. Because there are no batteries and charge controllers, they are less expensive and easier to maintain [23].

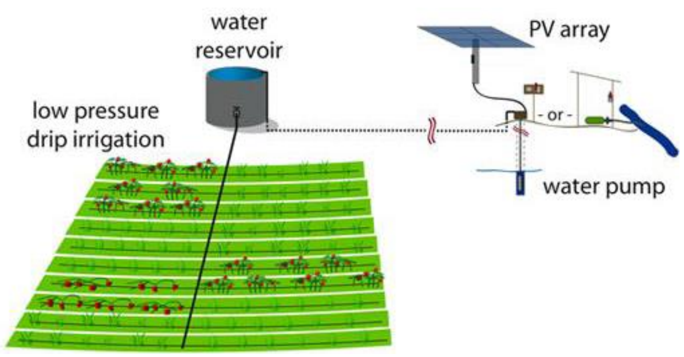

Figure 2.3. Examples of stand alone PV systems without storage battery [23].

2.1.2. Stand- Alone PV Systems With Battery Storage

A simple stand-alone PV system converts solar energy into electrical energy and stores it in batteries. Thanks to the rechargeable batteries, this stored energy can be used even in periods of unavailability or absence of solar radiation. Roof systems are the best suitable example of such systems. As shown in Figure 4, it consists of solar modules that produce electricity connected to the battery through the charge controller. An inverter is connected to turn direct current (DC) into alternating current (AC) to meet the needs of AC loads. These systems use rechargeable and dischargeable batteries several times [24].

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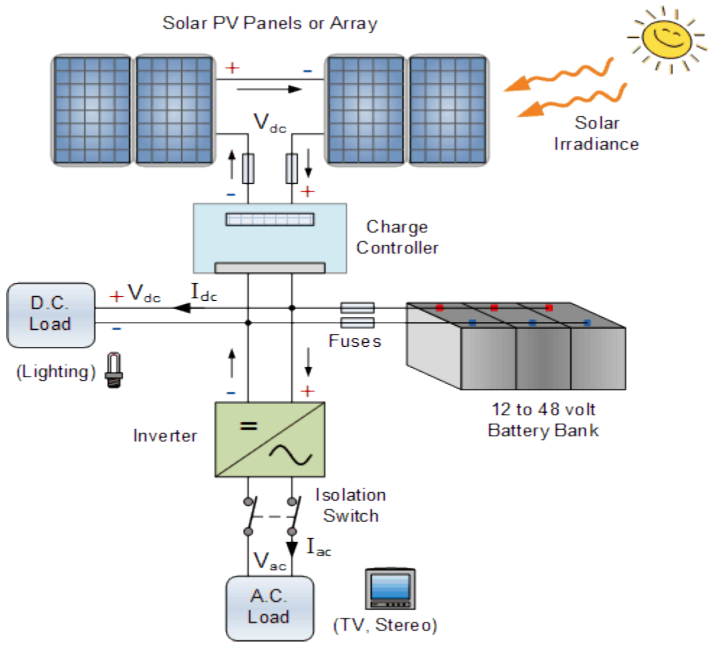


Figure 2.4. Examples of stand alone PV systems with storage battery [24].

2.1.3. On-Grid PV System

An on-grid PV system, is an electricity generation system connected with a public grid. A grid-connected photovoltaic system consists of solar panels and one or more inverters. This system passes the excess energy to the grid to which it is connected. Grid-connected systems vary in size from kilowatts to megawatts. In the case of systems connected to the residential grid, the extra is fed only into the public network in case there is an excess of power. Feeding the photovoltaic energy generated in the public grid requires converting DC to AC by a special inverter. The role of the grid inverter is to provide synchronization with the frequency of the general grid, and to regulate the voltage so that it does not exceed the network voltage [25].

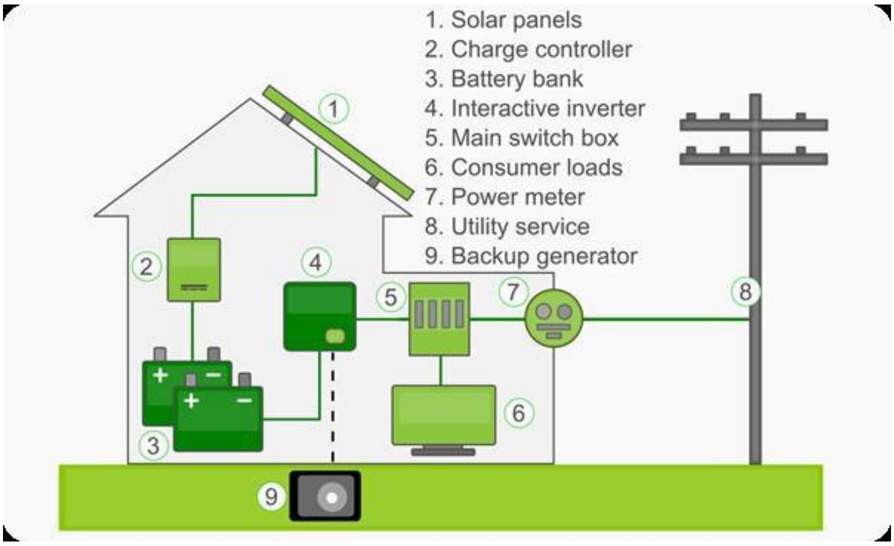


Figure 2.5. On grid PV system [23].

2.1.4. Hybrid Systems

Hybrid power systems combine two energy saving sources and are an ideal solution to improve performance and reduce cost. Hybrid power plants incorporate at least two different types of energy. It is common practice to combine diesel generators with renewable energy systems or to combine solar and wind energy systems with or without storage [23].

2.1.5. Building Integrated PV Systems

In this system photovoltaic modules are integrating into the building, such as the roof or facade. So that it is a building envelope and a source of energy at the same time. It can reduce construction costs, provide energy for the building, and contribute to reducing emissions. Building Integrated PV systems can be used in the building as stand alone or connected to the network. Its advantage is that with the policy of cooperative facilities, the storage system is basically free. It also benefits both the building and facility owner from the on-grid Building Integrated PV Systems [26].

2.2. PV/T SYSTEMS

Cooling the photovoltaic modules leads to an improvement in the efficiency of these modules. Reusing the thermal energy generated in the units is the best designs and enhancement the efficiency of the designed system as a whole, and this gives an encouragement for the development of the hybrid solar energy system [27]. Studies on PV/T began in the seventies of the twentieth century, and were aimed at improving the productivity of photovoltaic units. Higher system temperature reduces the efficiency of the energy produced. PV/T technology uses this waste heat for use in other areas such as hot water or hot air and to achieve system cooling to keep efficiency at reasonable levels [28,29]. Figure 2.5 shows a diagram of a PV/T collector concept.

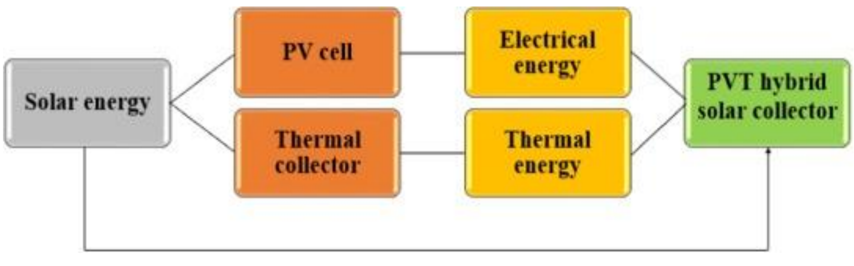


Figure 2.6. A schematic diagram of a PV/T collector conception [30].

Figure 2.6 illustrates the main applications used in PVT systems. Advantages of PV/T systems include: [31]:

- It can be used for several purposes as it can gain thermal and electrical energy with one another from one system.
- A higher efficiency can be achieved if two separate systems are used.
- It is possible to obtain suitable thermal energy for domestic applications according to the season.
- It can be added or integrated into the buildings, and this leads to a shortening of the cost recovery period.

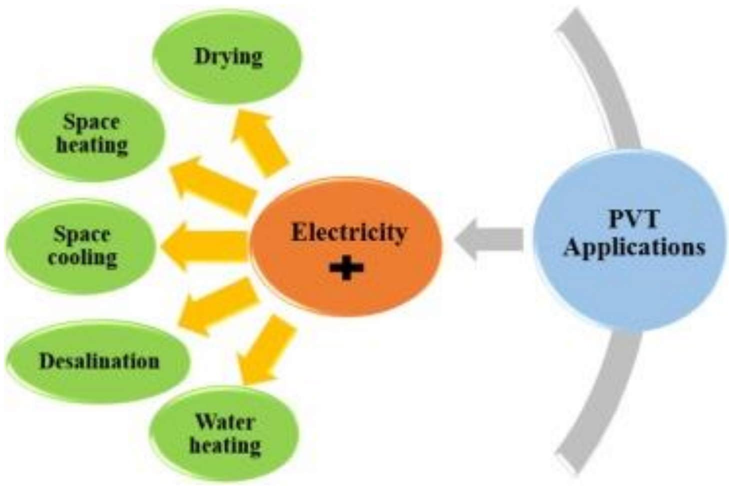


Figure 2.7. Main applications used in PV/T system [30].

PV/T systems are classified depending on the type and design of the PV module, the type of fluid used to remove thermal energy, and solar radiation is concetrated or not Figure 2.8. According to that; PV/T collectors are; PV/T liquid flow collectors, air circulating PV/T collectors, concentrating PV/T collectors and collective PV/T collectors [32]. Hybrid solar collectors can produce both electrical and thermal energy at the same time. These collectors mainly consist of a glazed or unglazed PV layer in the upper part and an endothermal layer below it. The absorbent layer contains an inlet and outlet for the liquid that is used to transfer heat.[27]. Figure.2.9 displays a simple assembly of flat plate PV/T collector.

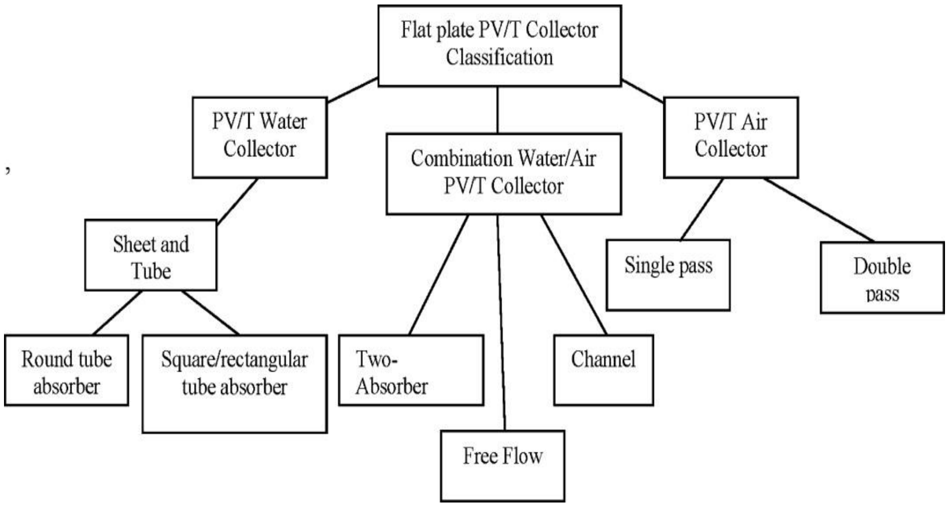


Figure 2.8. Classification of flat PV/T collectors [33].

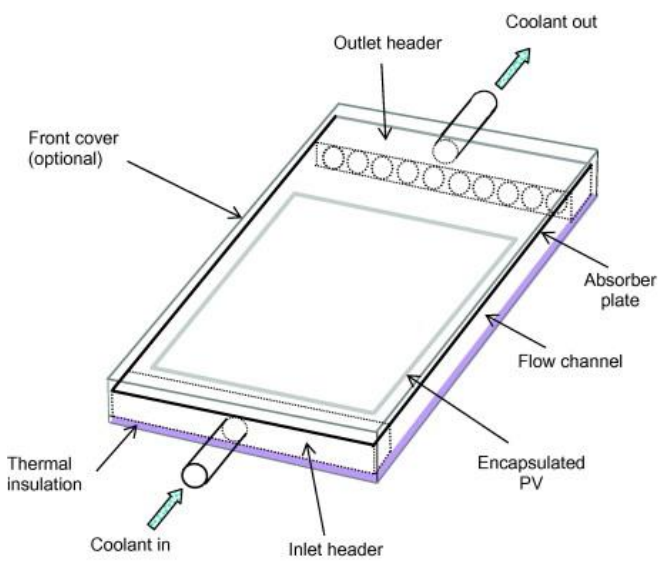


Figure 2.9. Assembly of a flat plate PV/T collector [34].

2.2.1. PV/T Air Collectors

In PV/T air collectors, the air is circulated through the accumulator. These collectors are suitable for hot air applications. One of their advantages is that they are cheaper and uncomplicated compared to PV/T water collectors. A fan is used instead of a water pump. There is no danger of freezing or boiling in extreme weather conditions. One of its main disadvantages is the low thermal performance due to the low thermal conductivity and heat capacity of air compared to water, as well as the low density of air that requires a high transfer volume [27]. Figure 2.10 shows a flat plate PV/T air collector.

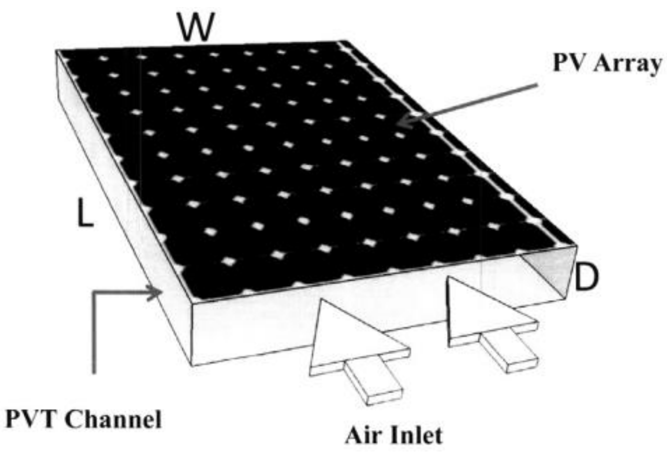


Figure 2.10. PV/T air collector [27].

2.2.2. PV/T Water Collectors

These collectors are suitable when there is a request for hot water, as water or a mix of water is circulated to transfer heat from the collector. Hot water can also be stored in special tanks for a certain period of time, so there may be defects such as leakage and freezing in some conditions [27]. The absorber layer consists of a tube in contact with the photovoltaic panel. PV/T water collector can have a higher efficiency compared to air collectors because of the higher heat capacity of water compared to air [35].

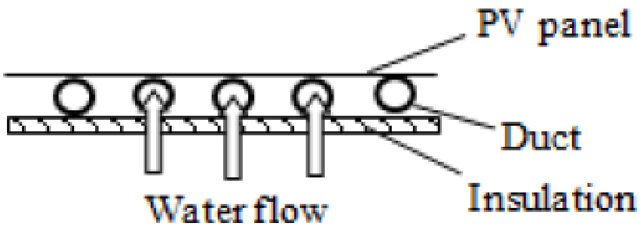


Figure 2.11. PV/T water collector [35].

2.3. CONCENTRATED PV SYSTYMS

Two types of system are used to benefit from the thermal and electrical energy of solar radiation: the system based on concentrating or gathering the solar radiation and the system without concentrating. Non-concentrating systems are called thermal photovoltaic systems, in concentrating systems, the solar radiation are concentrated to produce additional electricity from the panels used [36]. One of the advantages of concentrated photovoltaic energy systems is the low cost [37], because of the concentration of radiation, the space required for cells is less [38], and like the rest of the photovoltaic systems, they do not emit any harmful emissions, but the concentration leads to an increase in temperature, which negatively affects the efficiency of cells [39]. Concentrated PV systems have been modified to take advantage of thermal energy and are called Concentrated PV systems. They use low-cost optical elements. The heat generated on the photovoltaic cell is used to increase the efficiency of the system (electrical and thermal) to about 60-80% [40]. This will further complicate the system as the heat must be removed from the concentration area.

2.3.1. Types of Concentrated Photovoltaics

- Low Concentration PV: in low concentrated PV systems with a solar concentration less than 10 suns [41], cells usually do not require cooling because the heat flux is low. Studies and experiments have shown that if the concentration level is low no tracking or even cooling adjustments are required. Simple booster inverters are used in low-concentrating PV systems, which help increase output by more than 30 percent when compared to non-concentrating PV systems [42].
- Medium Concentration PV: in low concentrated PV systems with a solar concentration less than 10 suns [41], cells usually do not require cooling because the heat flux is low. Studies and experiments have shown that if the concentration level is low no tracking or even cooling adjustments are required. Simple booster inverters are used in low-concentrating PV systems,

which help increase output by more than 30 percent when compared to non-concentrating PV systems [42].

- High Concentration PV: the concentration factor of these systems is greater than 100, with this percentage of concentration the material of the cells decreases significantly, for example if we have a system with a concentration of 500, it can produce a cell with an area of 2 cm² the same as the production of a system with an area of 500 cm², but the cells must be able to withstand the working conditions Where a cooling process is required [41].

There are few kinds of concentrated solar plants:

- Linear Fresnel: in this type flat or slightly curved mirrors arranged in rows, reflect the sun rays to linear receivers fixed on towers.

Figure 2.12. Linear Fresnel collecto [43].

- Tower: in this type an array of heliostats (large mirrors on two tracking axes) that focus sunlight onto a receiver fixed in the top of the tower.

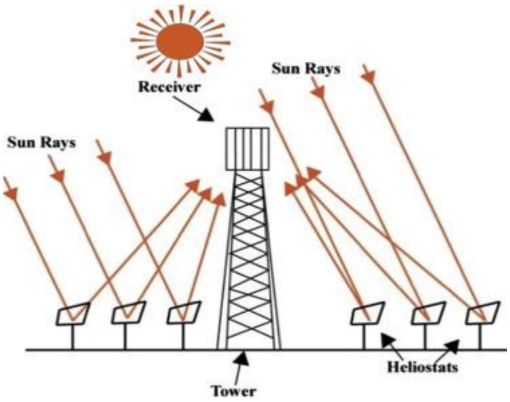
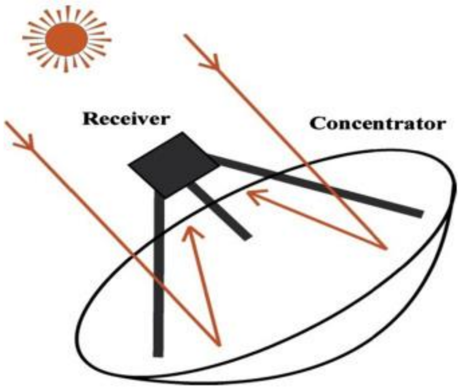


Figure 2.13. Solar tower [44].

- Dish: A parabolic dish with two axes traces the sun's rays to a point receiver.



a parabolic-dish concentrator [44].

- Trough: This is the most widespread. The sun is traced from east to west using parabolic mirrors [45].

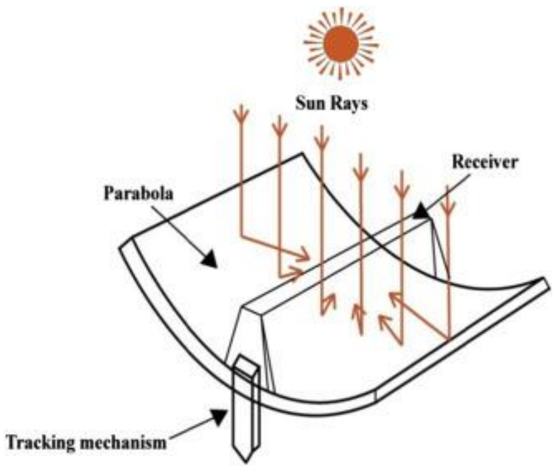


Figure 2.14. Trough solar concentrator [44].

2.4. PHOTOVOLTAIC EFFECT AND PHOTOVOLTAIC CELLS

Sunlight is converted into electricity using a technology named photovoltaic (PV). The name is consisting of two parts, photo meaning light, voltaic meaning electricity. PV cells or solar cells are devices made of semiconductors, that can convert the light that comes from sun to electricity [23]. Photovoltaic effect is the way that solar cells within convert light into electrical power. The first appearance of the photovoltaic effect was in 1839 by Edmond Becquerel. These solar cells are made of two different kinds of semiconductors joined together to make a p-n junction. When these two different types of semiconductors are joined together, an electric field is created in the junction. This created field causes the movement of negatively charged particles, electrons to the positive side and positively charged particles, holes to the negative side, in one direction and in another direction [46,47] as seen in Figure 2.3.

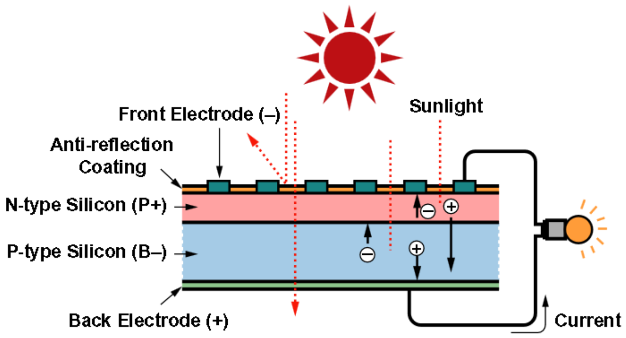


Figure 2.15. A section illustrates the photovoltaic effect [4].

Photovoltaic cells or PV cells can be fabricated from different materials in many ways, silicon is commonly used for solar cells, and it is plenty on earth and has semiconducting properties. PV cells are divided into three types based on silicon material case and quality, these three types are marketed and produced, Figure 2.4. [48]:

- Monocrystalline silicon solar cell.
- Polycrystalline silicon solar cells.
- Amorphous silicon /Thin film solar cell.

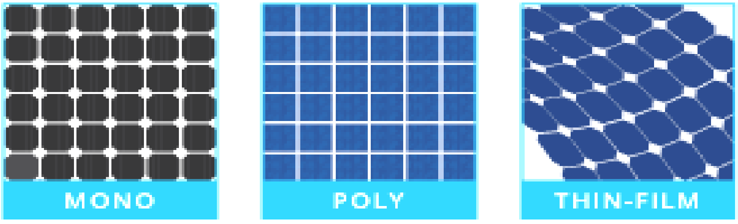


Figure 2.16. Solar cells types [49].

2.5. PHOTOVOLTAIC TECHNOLOGIES

Silicon is one of the most abundant elements in nature after oxygen, and this substance is the main element that goes into the manufacture of solar cells [48].

2.5.1. Monocrystalline Silicon Technology

Using this technique, an efficiency of more than 25% can be achieved in the laboratory [50]. According to the processing and manufacturing method, the practical efficiency that can be reached ranges from 15-22% [51]. The Czochralski process, created in 1916 is used to produce monocrystalline silicon cells [52]. Small amounts of parts per million of substances such as boron or phosphorous are added to the cell in order to change the electrical properties of pure silicon because it has low electrical conductivity. Depending on the material that was added, silicone of type n or p is obtained. The color of the resulting cells varies according to the method of treatment, and the color is often dark blue or tends to black [53].

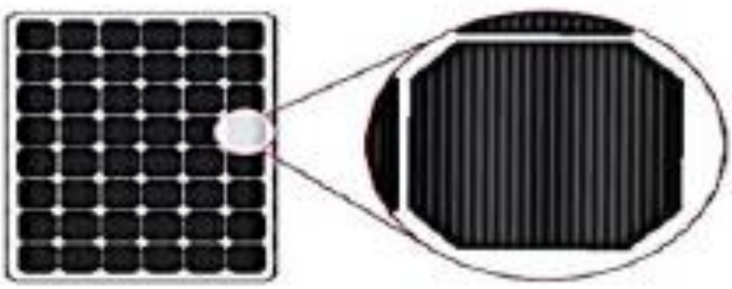


Figure 2.17. Monocrystalline solar cell [54].

2.5.2. Polycrystalline Technology

It is another crystalline silicon technology, in 1984 an efficiency of less than 15% was reached in the laboratory, and at the present time an efficiency of 22.3% has been reached under laboratory conditions [50], and a practical efficiency ranging from 14-20% [51]. This efficiency is low compared to the monocrystalline technology, and the production costs of this technology are low. After melting, the silicon is poured into a graphite box and cooled, and then the cell is made in the form of flakes [55]. A polycrystalline cell is shown in Figure 3. The color of the polycrystalline cell varies depending on the method of treatment and is usually blue [53].

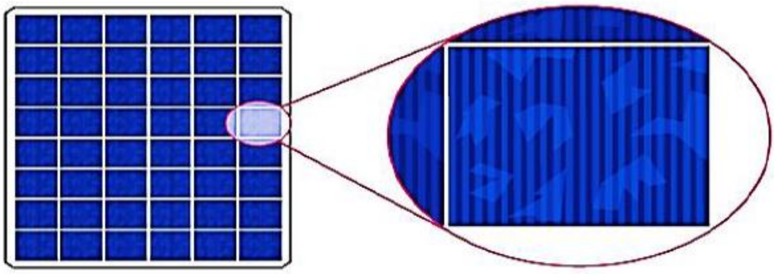


Figure 2.18. Polycrystalline solar Cell [54].

2.5.3 Thin Film Technologies

Compared to crystalline silicon, thin film PV modules use fewer materials and processes to obtain them, this technology is very thin around 35 to 260 nm. Despite the low cost of its production, its efficiency is low, and to compensate for this defect in its characteristics, it operates in low radiation conditions and has the advantage of flexibility, aesthetic character and light weight. Thin film photovoltaic cells have three technologies used in the market: Amorphous Silicon, CIGS (Copper Indium Gallium and Selenide) and CdTe (Cadmium Telluride) [53]. The efficiency ranges and cost estimations of commonly available solar PV modules are presented in Table 2.1.

Table 2.1. Efficiency ranges in three types of solar cells [56].

Polycrystalline	Monocrystalline	Thin film
reaches15-17% efficiency low cost	reaches 20% efficiency higher costs aesthetics	reaches ~11% efficiency portable and flexible lightweight aesthetics

2.6. PV MODULE AND ARRAY

The prime part of the photovoltaic system is the photovoltaic cell, the cell voltage is less than 1 V and not suitable for most applications, its shape is not mechanically strong and needs to be protected and encapsulated for applications. In the end, the basic unit reaches the user, which consists of many connected cells to gather and laminated and protected for practical use to obtain more current and voltage in proportion to the used applications [22,57], where a single cell produces a voltage of up to 0.5 V and a current ranging between 2 and 5 A, and that depends on the dimensions of the cell and the intensity of the radiation falling on it [58,59]. Most of the units in the market have 6, 12, 24, 48 V. When the modules are connected in series, the strings are formed, and the PV array is made from connecting the strings Parallel with each other and it represents all the modules in the PV system [60].

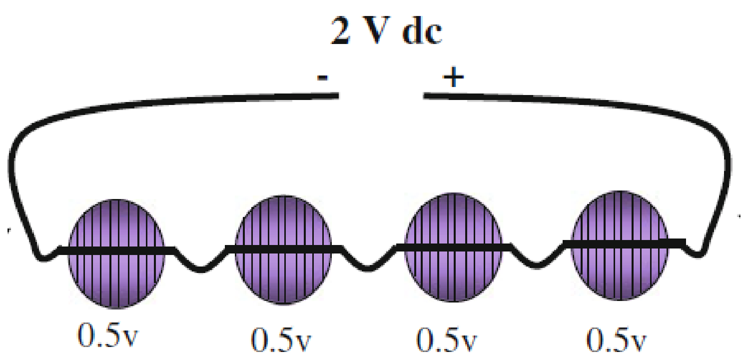


Figure 2.19. Cells connected in series [60].

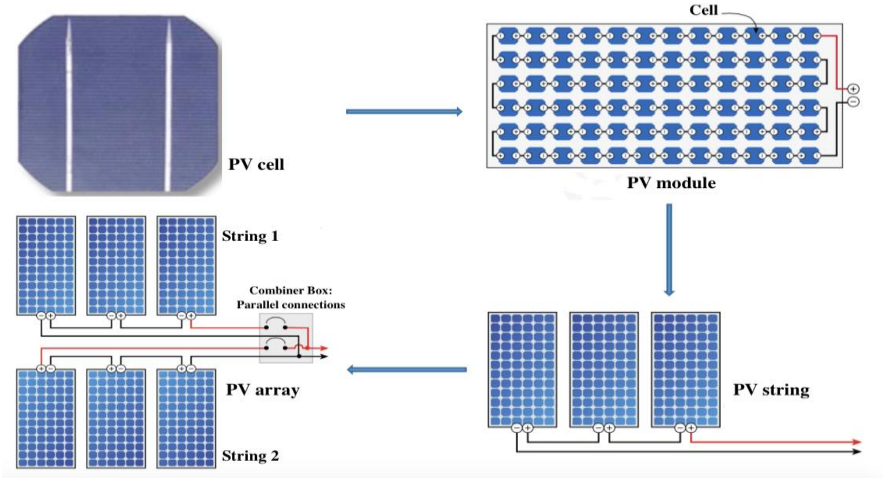


Figure 2.20. From PV cell to PV array [61].

2.6.1. PV Module Parameters

The performance of the photovoltaic module is evaluated through the IV and PV curves, where the electrical parameters of the module are short Circuit Current (I_{sc}), the max value of current that can be got when the solar PV module operates in standard test conditions (STC, $G = 1000\ W/m^2$, AM 1.5, $T_C = 25°C$). Open circuit voltage (V_{oc}): is the value of the voltage measured under STC operating conditions by placing the PV module in the open circuit mode. Maximum power point (MPP): maximum power that PV cell can produce at a given point, and this point is named as the maximum or peak power point is seen in Eq. (2,1) [62]. The recorded values of voltage and current recorded at this point are named as the maximum voltage V_m and the maximum current I_m and the module efficiency can be written as in Eq. (2.2) [62].

$$P_{max} = I_m * V_m \tag{2.1}$$

$$\eta_m = \frac{I_m * V_m}{G * A_m} \tag{2.2}$$

A_m the module area (m^2). The fill factor (FF) of the PV module is an important parameter. FF is the ratio of the peak power of the PV module to the output of the open circuit voltage (V_{oc}) and the short circuit current (I_{oc}) as in Eq. (2.3). Formally,

FF is the scale of the characteristic curve IV of the PV module, given by area. The FF, for a good solar module, varies between 0.76 and 0.8, the FF of the solar PV module determines its quality [23,31].

$$FF = \frac{I_m * V_m}{I_{sc} * V_{oc}} \tag{2.3}$$

Maximum power can be written in terms of fill factor as in Eq. (2.4).

$$P_{max} = FF * I_{sc} * V_{oc} \tag{2.4}$$

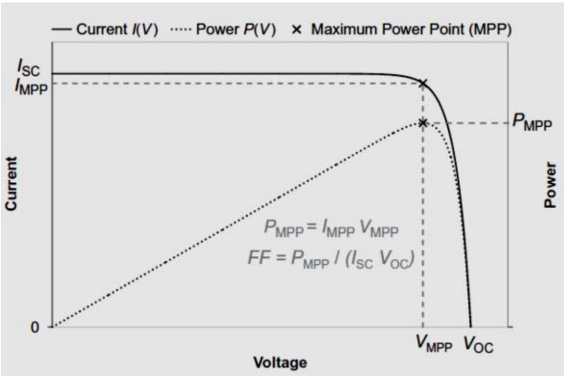


Figure 2.21. I-V and P-V curves [62].

The PV module voltage is related to the temperature of the cells inside the unit. This relationship is inversely proportional because the voltage decreases with temperature increases. Likewise, as the temperature decreases, the voltage increases. This is an important consideration as their voltages change based on these temperatures. The amount of change is indicated by the voltage temperature coefficient. This value is often taken as a percentage per Celsius degree (%/°C). Temperature coefficient for V_{oc} is $-0.35\%/°C$ [63].

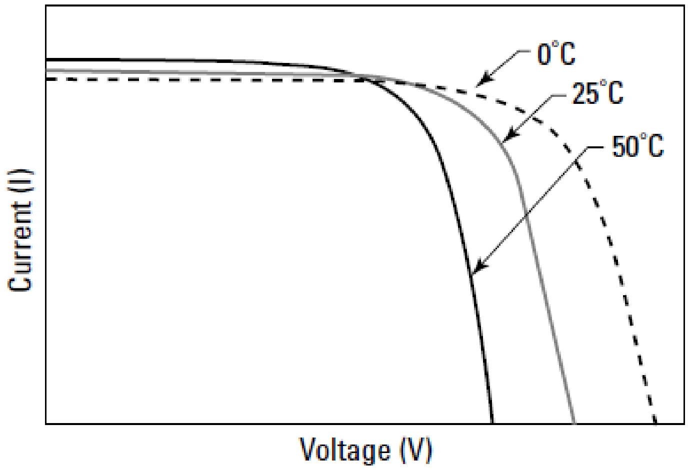


Figure 2.22. Current and voltage dependence on cell temperature [63].

Cell temperature can be theoretically determined with Eq. (2.5) depending on the ambient temperature [59].

$$T_c = T_a + \frac{NOCT-20}{800} \times G \quad (2.5)$$

Where T_a ambient temperature, T_c cell temperature. $NOCT$ is the nominal operating cell temperature, it is outlined as the temperature degree which module reached in operation conditions of 800 W/m^2 radiation, 1 m/s wind speed, 20°C ambiance temperature, and load less operation [57]. The current increases when the radiation increases and the voltage is slightly affected. The current at any other radiation G is given as in Eq. (2.7) [16].

$$I_{sc} = \frac{G}{G_o} * I_{sc(G_o)} \quad (2.7)$$

Where G The radiance of the current will be determined at, G_o is STC solar radiation, $\mathrm{I_{sc(G_o)}}$ is STC Short circuit current.

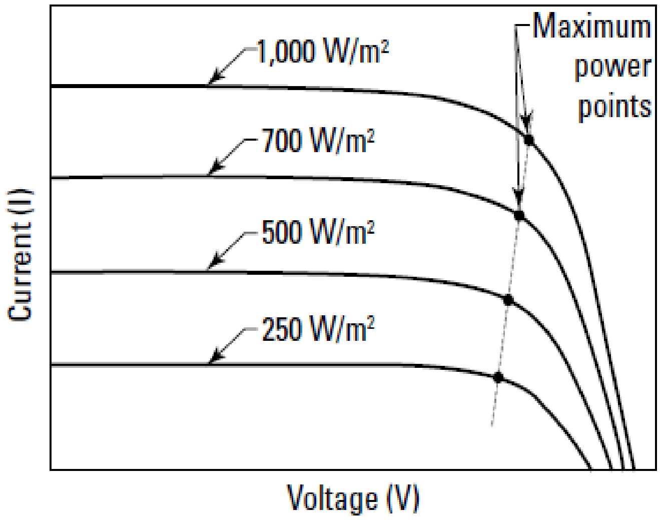


Figure 2.23. Changes in current and voltages according to solar radiation [63].

The module electrical efficiency can be classified as module and cell efficiency, the cell efficiency is given by Eq. (2.8) and module efficiency by Eq. (2.9) [63].

$$\eta_c = \eta_o[1 - \beta_o(T_c - 25)] \quad (2.8)$$

$$\eta_m = \eta_c * \tau * \alpha * PF \quad (2.9)$$

Where η_c the cell efficiency at T_c, η_o cell efficiency at standard test conditions, β_o Thermal coefficient of electrical efficiency (depends on the materials used to manufacture PV module, it is 0.0045/K For crystal silicon) [26]. τ_c.the transparency for the module glass (approximately 90% for polycarbonate), α_c the solar cell absorptivity (approximately 95%), PF Packing factor which is outlined as the ratio of total cells area to module area [64,65].

2.7. SUN RADIATION MEASUREMENT

The following instruments are commonly used in the measurement of solar radiation on the earth's surface:

2.7.1. Pyranometer

The pyranometer is prepared for global radiation measurement. It is normally used to measure irradiation on a horizontal fixed surface, and also used in measuring the global radiation on an inclined surface of PV collectors [16].

2.7.2. Pyrheliometer

Pyrheliometer is a device used to measure direct sunlight. This device is placed together with the solar tracker system in a way to keep the solar radiation constantly upright on the surface [66].

2.7.4. Solar Meter

This device measures direct solar radiation, and it's cheaper in comparing with other devices [15].

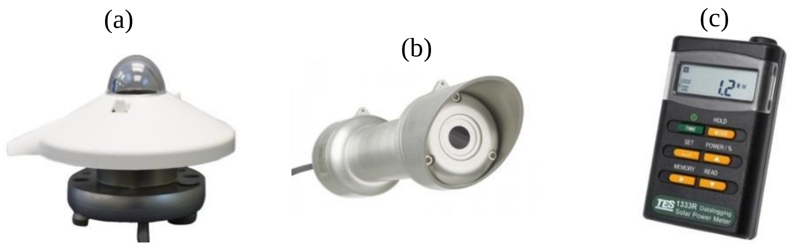


Figure 2.24. (a) Pyranometer, (b) Pyrheliometer, (c) Solarmeter [15,67,68].

PART 3

LITERATURE

As known, the main object of solar panels is to produce electrical energy, as solar cells use photovoltaic technology to convert light energy into electricity, and this is done with an efficiency that mainly related to the type of used solar cells. The energy that panel receives is not completely converted into electricity, more than 80% of the solar radiation that reaches the panels is not transformed into electrical energy but is reflected or switched into thermal energy [69]. The generated thermal power negatively affects the electrical energy conversion parameters of the panels, because it increases the temperature of cells, as the efficiency decreases by 0.4-0.5%/°C, and this inverse relation between the conversion efficiency and the temperature because of the dependence of open circuit voltage on temperature and affected by it [70]. The importance of cooling solar panels appears at present due to the sensitivity of cells to high temperatures and its effect on their performance [71]. When the PV panel performance parameter is determined, this process is done in standard test conditions (STC), these parameters change when the cell or the panel works under different operating conditions where the temperature of the panel or cell may rise to 70°C in practical applications. Several systems developed by researchers aim to decrease the effect of temperature on solar panels. These can be categorized into two classes, passive and active cooling systems, in active cooling systems additional devices are used like pumps or fans to circulate coolant used to transfer heat, in the passive cooling systems don't need like these devices but may require additional parts like heat sink at behind the panel [72]. Figure 3.1 shows the different technologies for active and passive cooling of solar panels [73].

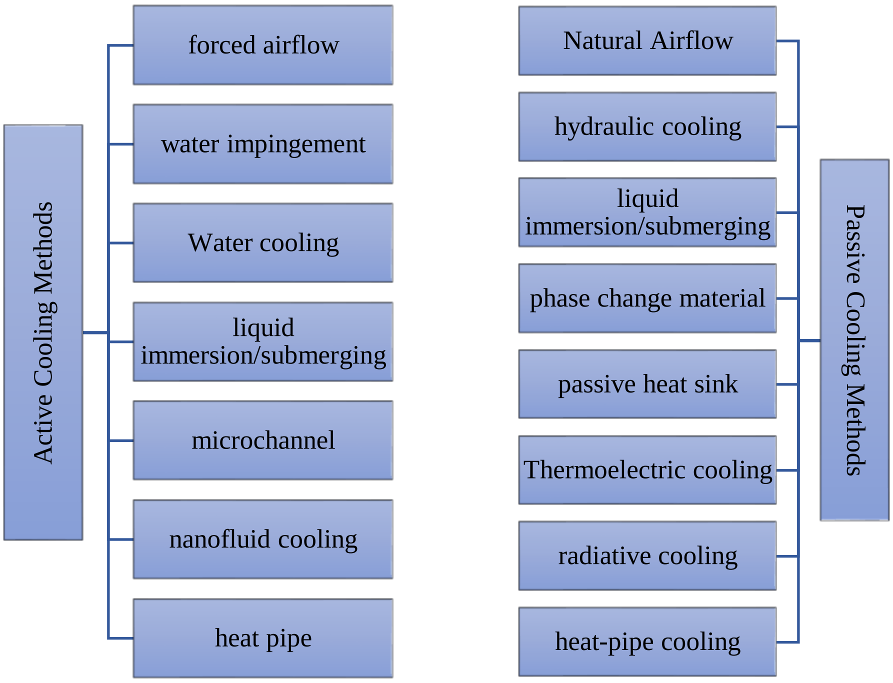


Figure 3.1. PV module cooling methods [73].

Appling phase change materials in different cooling systems have been used recently as a way to enhance thermal and electrical performances, by using PCM on the back side of the PV module. The classification of phase change materials has been briefly summarized in Figure 3.2 [74].

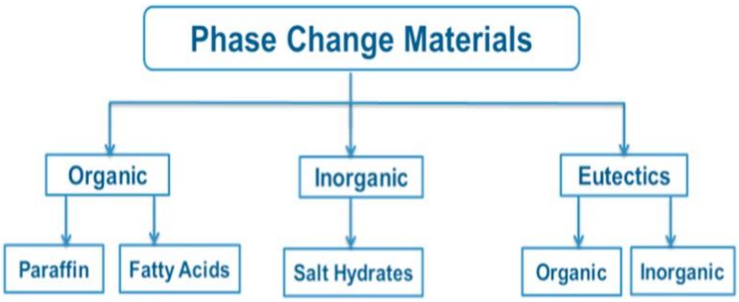


Figure 3.2. Broad classification of PCM [74].

PCMs are organic, inorganic, and eutectics products that change their case depending on melting temperature [75]. The latent heat of the PCM is used to keep the PV panel at a nearly steady temperature. The stored heat can be used later for many purposes to improve the efficiency of the whole system like space heating, water heating, and others [76]. Researchers used one or more of these technologies to obtain a lower operating temperature and improve efficiency.

Bahaidarah studied numerically and experimentally the results of the active method using water to cool the module. The module temperature went down to about 20% and the PV module efficiency increased by about 9% [77].

Krauter et al. circulated water on the surface of integrating concentrated PV panels. The results showed that applying circulating water over surfaces enhanced PV efficiency by about 10% [78].

Gotmare et al. studied passive cooling using fins, natural convection. As the results showed, by using fins the PV panel measured temperature decreased and the gained power was enhanced by 5.5% [79].

Bayrak and Selimefendigil et al. showed in their studies that adding fins to the PV panel helps to decrease temperatures of its surface and increase efficiencies [80,81].

Mays et al. experimentally analysed the performance of PV modules using an aluminium finned plate. Results came out with that, using of finned plate of aluminium has improved the electrical efficiency by 1.75%, and the produced power by 1.86 W [82].

Yuan et al. studied a simulation of heat transfer with and without PCM, electrical efficiency is improved by 12.1%, and 11.9% with PCM and without respectively [83].

Su et al. used an air cooling technique with PCM and got a 10.7% improvement in the module efficiency when the ambient temperature was 28-37°C [84].

Sathe and Dhoble added fins to PCM in the simulation study and applied them to the back of the PV module, the results came out that the PCM temperature was lower by 18% [85].

Rajvikram et al. used a PCM aluminum box to get lower temperatures for PV, the solar radiation was 1000 W/m^2, and ambient temperatures were 25-31°C. The temperature was reduced about 10.35°C, and the module efficiency improved by 2% [86].

Sardarabadi et al. experimentally studied a ZnO-nanofluid based with paraffin as a PCM applied to PV/T collector. The nanofluid pass into pipes inside the PCM tank. The use of these techniques has increased the output electricity of the PV/T by 13% [87].

Soliman et al. designed an experimental setup to verify the effect of using a heat sink on the behavior of solar cells. The study is conducted inside with different values of solar radiation. The cooling heat sink is done by using forced and natural air. The results showed that the temperature of the solar cells was reduced by 5.4%, and 11% by using natural air and forced air to cool the heat sink, respectively. The power increased by about 16%. [88].

Michelia et al. computationally studied the behaviour of PV module by plate micro fins in their cooling system. The results showed that when micro fins system was applied to the solar cells, the thermal performance is improve, and the produced power increased by 50 % [89].

Popovici et al. computationally studied the behavior of the solar cell with an air cooling heat sink system. The results showed that using the air cooling heat sink system decreases the cell temperature, and increased efficiency and power [90].

Suleiman and Hassan used heat sinks and micro channels to test the performance of solar cells. By using this system, they found an increase in cell efficiency and power of 8% and 13%, respectively [91].

Rajput and Yang studied the use of cylindrical finned heat sinks to cool plates. Using a pin fin heat sink. The results achieved a temperature drop of 58.4°C with the heat sink [92].

Al-Zaabi et al. gained an enhancement in electrical efficiency of approximately 15-20% by comparing PV panel and PV/T water collector to investigate the improvement in the efficiency, and obtained values close to 60% in thermal efficiency [93].

Mousavi Baygi and Sadrameli studied using a box polyethylene glycol 1000 to cool the PV panel. The temperature went down from 62°C to 47°C. The efficiency improved by 8% [94].

Li et al. used paraffin wax in cooling the PV module, and showed that the temperature difference of PV and PV/PCM can reach 23°C, and the output power of PV/PCM system increased by 5.18% [95].

Abdelrahman et al. used RT35HC as a PCM mixed with (Al_2O_3) nanoparticles. Results found that using PCM or PCM reinforced with nanoparticles in PV panels decreased the PV panel surface temperature, and good results were got when the number of fins was increased inside the PCM tank [96].

Sarikarin et al. studied a cooling PV module with PCM container supported by fins, he could reduce the temperature by 6.1°C and rise conversion performance by 4.86% [97].

Hachem et al. experimentally used and combined the thermal behaviour and electrical performance of PV panels. He found that the temperature reduction was about 6.3%, and the output of electric power increased by 5.8% [98].

Hasan et al. used paraffin placed in the PV panel back side, and the annual electrical yield of the PV-PCM enhanced by 5.9% [99].

Nada et al. experimentally tested three building-integrated PV modules installed in the same location and at the same time, pure PCM and PCM/Al_2O_3 nanoparticles were applied. The results came out with a temperature decrease of 8.1°C and 10.6°C, and an efficiency improvement of 5.7% and 13.2%, respectively. [100].

PART 4

THEORETICAL ANALYSES

The efficiency of modules can be evaluated depending on the two laws of thermodynamics.

Energy analyses:

Eq. (4.1) presents the general equation for energy balance.

$$\Delta\dot{E} = \sum \dot{E}_{in} - \sum \dot{E}_{out} \quad (4.1)$$

In Eq. (4.1) $\dot{E}_{in}$ and $\dot{E}_{out}$ are inlet and outlet energy to the system. The equation of general energy balance for PV module is represented in Eq. (4.2) and for PV/T collectors as in Eq. (4.3).

$$\dot{E}_{solar} = \dot{E}_{elec} + \dot{E}_{loss} \quad (4.2)$$

$$\dot{E}_{solar} = \dot{E}_{th} + \dot{E}_{elec} + \dot{E}_{loss} \quad (4.3)$$

Applied solar energy on the PV module and PV/T collectors can be written as in Eq. (4.4).

$$\dot{E}_{solar} = \mathrm{G}A_m \quad (4.4)$$

In Eq. (4.4) G is the solar irradiance, A_m is the total area of the module's surface. The electrical output power from PV and PV/T collectors can be evaluated with Eq. (4.5).

$$\dot{E}_{elec} = VI \quad (4.5)$$

The thermal energy gained from the PV/T collector with circulated air can be estimated with Eq. (4.6).

$$\dot{E}_{th} = \dot{m}_{air}.C_{p,air}.\left(T_{air,out} - T_{air,in}\right) \quad (4.6)$$

Electrical and thermal efficiency for PV module and PV/T collector can be determined in Eq. (4.7) and Eq. (4.8) [101].

$$\eta_{elec} = \frac{\dot{E}_{elec}}{\dot{E}_{solar}} \quad (4.7)$$

$$\eta_{th} = \frac{\dot{E}_{th}}{\dot{E}_{solar}} \quad (4.8)$$

According to the first law of thermodynamics, the efficiency can be calculated using Eq. (4.9).

$$\eta_{overall} = \eta_{elec} + \eta_{th} \quad (4.9)$$

Exergy analyses:

Exergy balance equation can be written as in Eq. (4.10).

$$\Delta\dot{E}x = \dot{E}x_{in} - \dot{E}x_{out} - \dot{E}x_{dest} \quad (4.10)$$

The exergy balance for PV module can be specified as in Eq. (4.11) and for PV/T collector as in Eq. (4.12).

$$\dot{E}x_{solar} = \dot{E}x_{elec} + \dot{E}x_{th} + \dot{E}x_{dest} \quad (4.11)$$

$$\dot{E}x_{solar} + \dot{E}x_{air,inlet} = \dot{E}x_{elec} + \dot{E}x_{air,outlet} + \dot{E}x_{dest} \quad (4.12)$$

Solar exergy can be written as in Eq. (4.13) [102].

$$\dot{E}x_{solar} = GA_m\left(1 - \frac{1}{4}\left(\frac{T_{ambient}}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{ambient}}{T_{sun}}\right)^4\right) \quad (4.13)$$

T_{sun} represents the sun temperature as 5777 K. Thermal exergies for PV module can be calculated as in Eq. (4.14), and the thermal exergy for PV/T collectors is given as in Eq. (4.15) [103].

$$\dot{E}x_{th} = \dot{E}_{loss}\left(1 - \frac{T_{ambient}}{T_s}\right) \quad (4.14)$$

$$\dot{E}x_{th,PV/T} = \dot{E}x_{air,outlet} - \dot{E}x_{air,inlet} \quad (4.15)$$

Eq. (4.17) gives the electrical exergy of PV and PV/T collectors which equals electric energy [104].

$$\dot{E}x_{elec} = \dot{E}_{elec} \quad (4.16)$$

Destruction exergy for tested module and collectors can be determined as in Eq. (4.17).

$$\dot{E}x_{dest} = \dot{E}x_{solar}(1 - \eta_{ex}) \quad (4.17)$$

The second law efficiency or exergy efficiency for PV module and collectors can be given as in Eq. (4.18) for PV and Eq. (4.19) for PV/T [105].

$$\eta_{ex,PV} = \frac{\dot{E}x_{elec} - \dot{E}x_{th}}{\dot{E}x_{solar}} \quad (4.18)$$

$$\eta_{ex,PV/T} = \frac{\dot{E}x_{elec} + \dot{E}x_{th,PV/T}}{\dot{E}x_{solar}} \quad (4.19)$$

PART 5

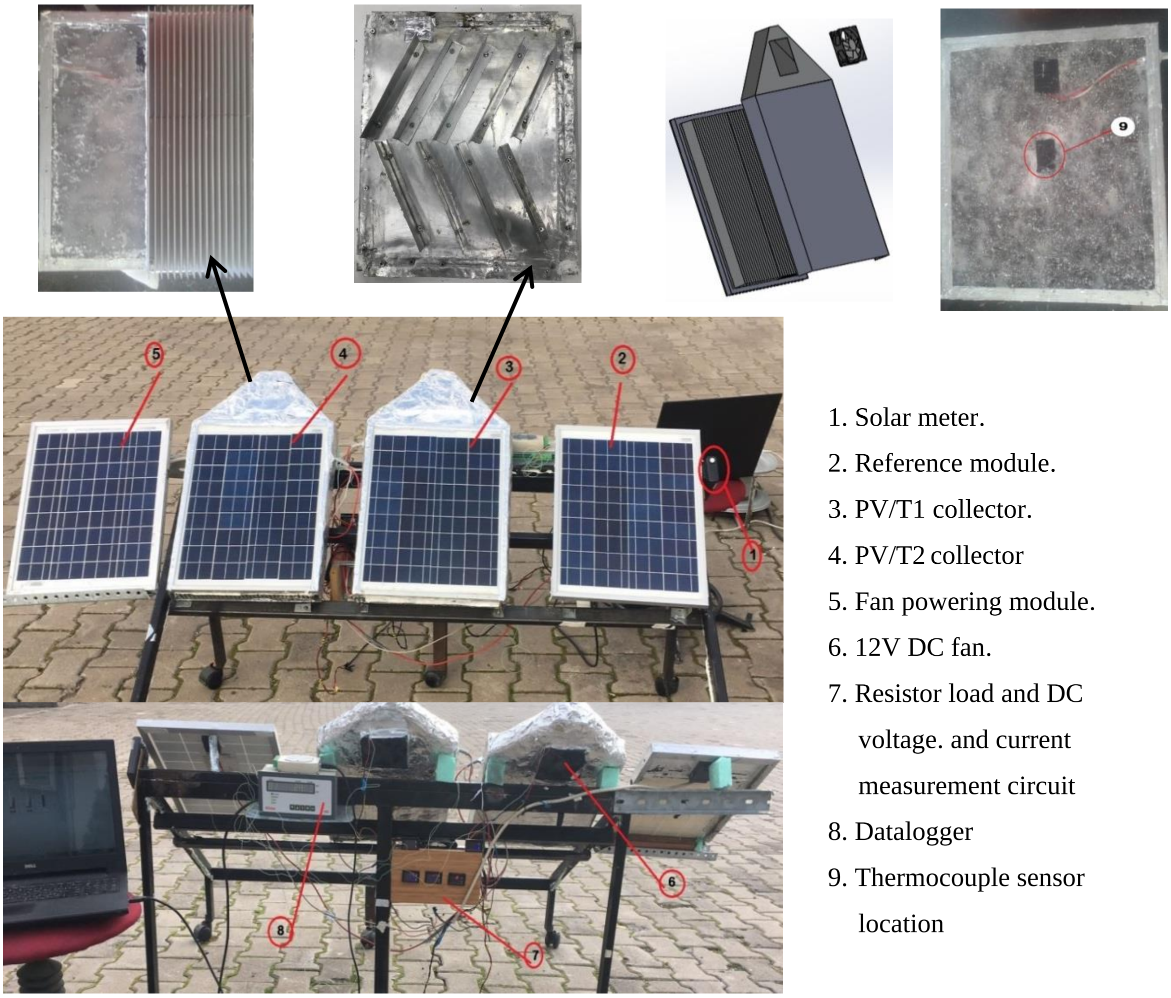
METHODS AND MATERIALS

This experiment was carried out at the University of Karabuk in October. Three 20 W solar panels were used to compare the results, their characteristics are shown in Table 5.1. Where the first panel was used as a reference (called PV) to compare the remaining two panels with it, paraffin (phase change material) was mixed with steel foam to increase the conductivity factor of paraffin. Steel foams were placed in the backspace of the second and third panels, then the paraffin was melted and the backspace of the two panels was filled with a thickness of one centimetre, and then an aluminium heat sink was installed to close the full size. In the second panel (PV/T1), the heat sink consisted of fins inclined at an angle of 60 degrees, four of them in the lower half of the plate and five of them in the upper half of it, opposite in direction. In the third panel (PV/T2), straight or flat fins were used parallel to the longitudinal direction of the panel. A cover is attached to the backsurface of the each PV/T collector to obtain air channel and the cover is isolated with ceramic fibre. The experiment setup is shown in Figure 5.1. Table 5.1 presents the used PV module characters.

Table 5.1. Main characters of modules used in the experiment.

Description	Properties
(P_{max}): Maximum Power	20 W
(V_{mp}): Maximum Power Voltage	18.5 V
(I_{mp}): Maximum Power Current	1.09 A
(V_{oc}): Open Circuit Voltage	22.68 V
(I_{sc}): Short Circuit Current	1.18 A
Dimensions	360×420×20 mm
Power Tolerance	0 to %5W

The experiment was carried out between 11:00 and 16:30. During the progression of the experiment, the solar radiation, voltage and current produced by the three panels, were measured at an interval of 5 minutes by a portable solar power meter and the voltage and current measurement circuit. The ambient temperature, panels’ surfaces temperature, and the temperature of the air coming out of each of the second and third panels were measured. The values of temperature were measured using six thermocouples (K-type) at an interval of 1 minute. Thermocouples were attached to the middle of the panel’s back surface, and one at the place of an outtake of air passing through the heat sink area.



1. Solar meter.
2. Reference module.
3. PV/T1 collector.
4. PV/T2 collector
5. Fan powering module.
6. 12V DC fan.
7. Resistor load and DC voltage. and current measurement circuit
8. Datalogger
9. Thermocouple sensor location

Figure 5.1. The experimental visualization.

The used devices in the experiment are listed in Table 5.2.

Table 5.2. Devices used in the experiment.

Parameter	Device name	properties
Solar radiation (W/m^2)	TES 1333R solar power meter	Irradiance: 0-2000 W/m2 , accuracy: ± 10 W/m^2 or ±5
Temperature (°C)	Type K thermocouple,	-40°C to +1200°C, Length 2m
	Elimko E680 datalogger	Operating conditions −5 to 55°C - 85–265 V AC Standard working limits −200 + 1300°C 16 channels.
Modules voltage and current (V, A)	14.7 ohm load,	20W aluminium resistance
	Digital DC volt ampere meter	Operating voltage: DC 4.5~30V Voltage measurement: DC 0 ~ 100V Current measurement: 1A ~ 10A

TES1333R solar meter installed at the same angle next to modules which are the latitude of the Karabuk 40°. Elimko datalogger was used to record values of measured temperature from K-type thermocouples. 14.7-ohm load was used to evaluate current and voltage values and displayed by digital ampere volt screens. Table 5.3 contains the thermophysical characteristics of Paraffin and steel foam.

Table 5.3. Thermophysical properties of PCM and steel foam.

Material	Paraffin		Steel foam
	Solid	Liquid	
Melting point (°C)	43		-
Latent heat (kJ/kg)	189		
Density (kg/m^3)	910	765	7700
Specific heat (J/kg°C)	2840	2540	480
Conductivity (W/m K)	0.23	0.21	25

PART 6

RESULTS AND DISCUSSION

PV module and PV/T collectors were studied experimentally in the period 11:00 - 16:30 on a sunny and clear day in October. The measured values were ambient temperature, modules' backside temperatures, air temperatures at the outlets of PV/T1 and PV/T2, solar radiation, voltage and current produced from modules.

Figure 6.1 shows the curve of change in ambient temperature and solar radiation with time.

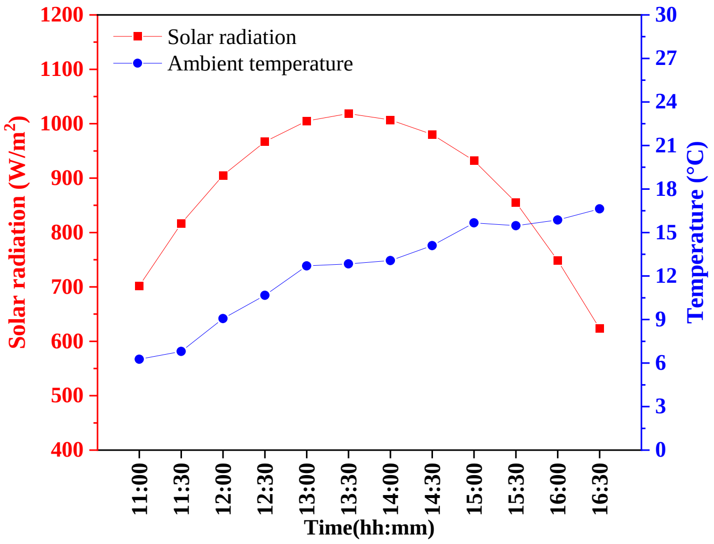


Figure 6.1. The temperature and radiation during the experiment.

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The temperature at the beginning of the experiment was 6.27°C, and the highest peak was recorded at the temperature of 16°C. The radiation when the experiment started was 702 W/m^2 and reached 1018 W/m^2 at 13:30, then it decreased afternoon to reach 623.5 W/m^2 at the end of the experimentation. The recorded temperature of modules' backsides is shown in Figure 6.2.

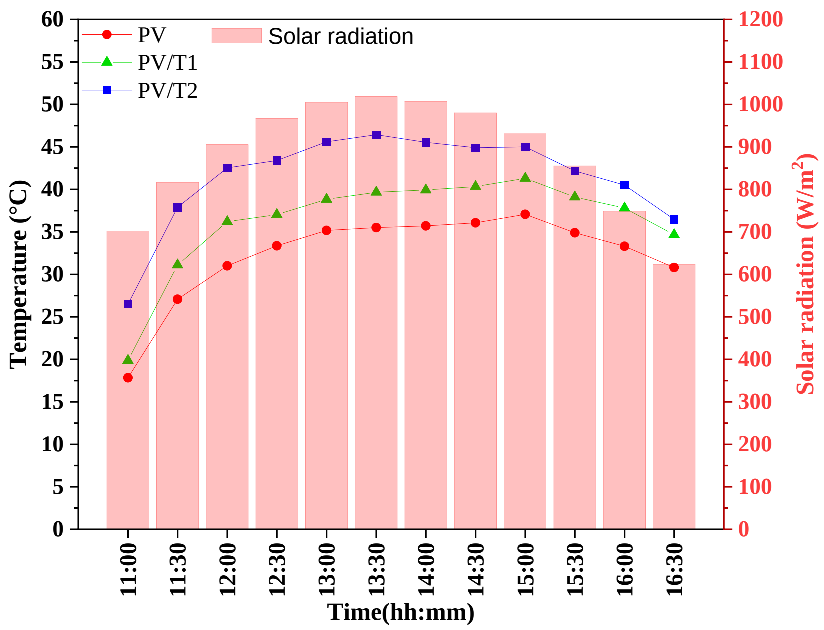


Figure 6.2. Ambient and panels temperature variations.

The solar radiation increment drives to raise the temperature of the panels directly. It increased for PV from 26.5ºC to reach 46.43ºC until noon and was 36.47ºC when the experiment is finished. While the highest backside temperature for PV/T1 reached 41.3ºC and went down to 34.67ºC at 16:30. The average temperature throughout the experiment period was 41.41ºC and 36.32ºC for PV module and PV/T1 collector respectively. While the temperature of PV/T2 collector increased, as it was the coldest, from 17.83°C in the morning, and the peak value reached is 37.07ºC and dropped to 30.8ºC at the end, with an average of 32.31ºC over the experiment duration. By comparing with the reference panel PV/T1 which was cooled by PCM mixed with steel foam and inclined fins heat sink, it was cooled by 12.29%, and the cooling rate for PV/T2 comparing to the reference panel was about 21.97%. More solar radiation means an increment in the amount of energy reaching the panels, and a part of this energy remains in the panels as thermal energy, causing an increase in their temperature which affect their produced electrical power and efficiency. The process of cooling applied on the panels controls the decrease in the electrical efficiency of the modules. In this experiment, an attempt was made to control the temperature rising and the decrease in electrical output through the process on PV/T2 and PV/T1. Current and voltage curves are given in Figure 6.3.

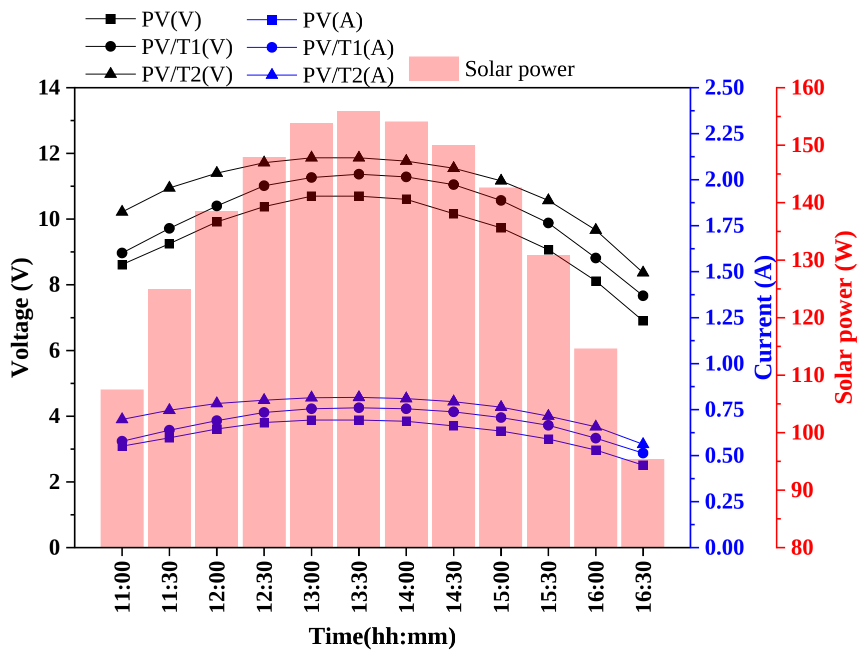


Figure 6.3. Current and voltage output from modules.

For the reference module its current and voltage were estimated as 0.55 A and 8.62 V at 11:00. At peak time they reached 0.69 A and 10.7 V and decreased to 0.45 A and 6.9 V at the end of experimentation. The average current and voltage during the testing time were 0.62 A, 9.51 V for the reference module. For PV/T1 and PV/T2 modules, where cooling methods were applied on, current and voltage values were 0.68 A, 10.17 V and 0.75 A, 10.93 V respectively. The recorded values for PV/T1 were 0.58 A, and 8.97 V at 11:00, they raised to 0.76 A and 11.37 V at noon, and have been recorded to 0.51 A and 7.67 V values at 16:30. The current and voltage values for PV/T2 were 0.69 A and 10.22 V at the beginning of the experiment, 0.82 A and 11.87 V at noon, 0.56 A and 8.36 V at 16:30. The electric energy produced from PV module and collectors is shown in Figure 6.4.

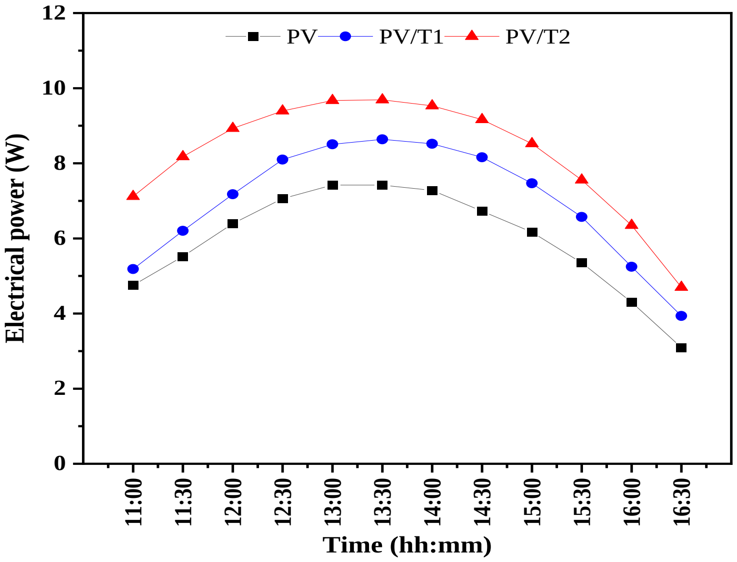


Figure 6.4. Electrical power of modules.

During the experimentation, the average electrical power was 6.98 W and 8.23 W for PV/T1 and PV/T2, respectively. Whereas the PV panel's produced electrical energy was the lowest because of the high temperature. The average time energy production was approximately 5.96 W. Compered to the references value it was determined that the power value is enhanced by 17% and 38%. Thermal powers for collectors are illustrated in Figure 6.5.

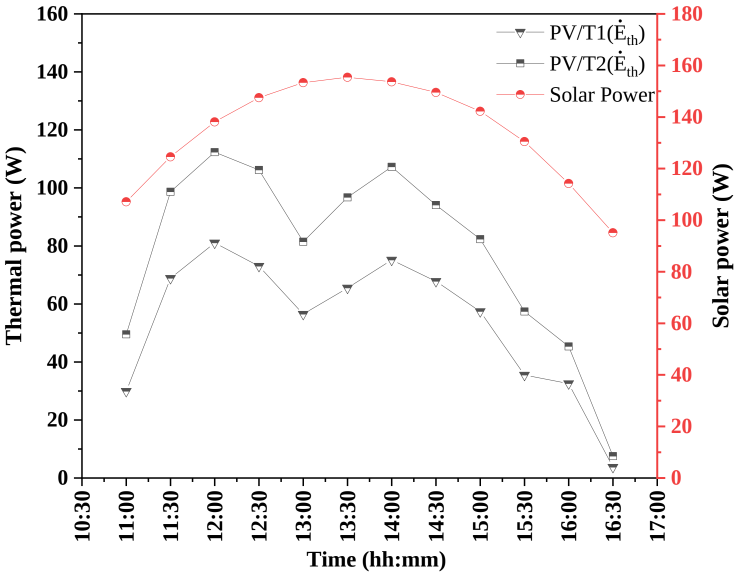


Figure 6.5. Thermal energy output of collectors.

Through the daytime, the heat load on the panels changes with the change of solar radiation, as it increases with the solar radiation increment, and then returns to decrease with its decrease. PV/T2 has higher cooling performance or produces higher thermal energy. The average amount of thermal power gained from PV/T collectors were 53.93 W for PV/T1 and 78.26 W for PV/T2 respectively. The energy carried by air can be applied for thermal purpose as drying. PV module and PV/T collectors' electrical efficiency curves are illustrated in Figure 6.6.

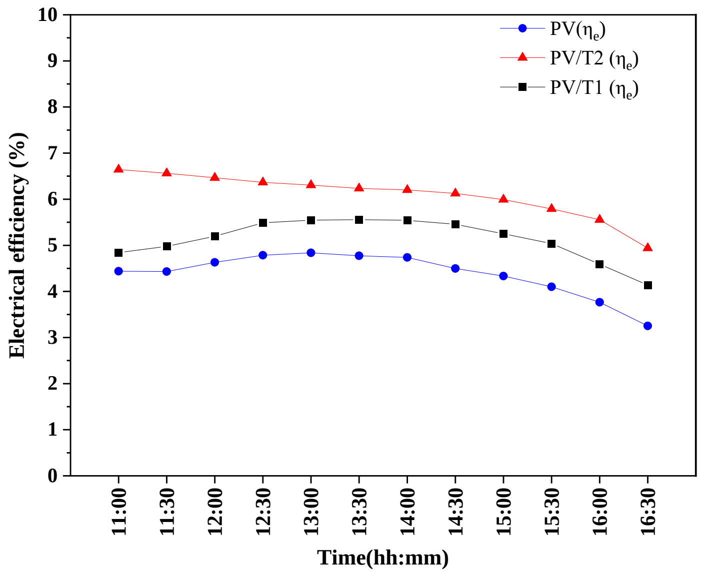


Figure 6.6. Electrical efficiency of the PV modules.

In our experiment, electrical, thermal, total efficiency, and exergy efficiency were calculated depending on the first and second law of thermodynamics. For the reference module, the time rate of electrical efficiency was approximately 4.37%. In PV/T1 with an average temperature between PV and PV/T2, the average electrical efficiency was approximately 5.12% and 6.08% For PV/T2 collector. The thermal and total efficiency over time for each of the PV/T1 and PV/T2 collectors are shown in Figure 6.7.

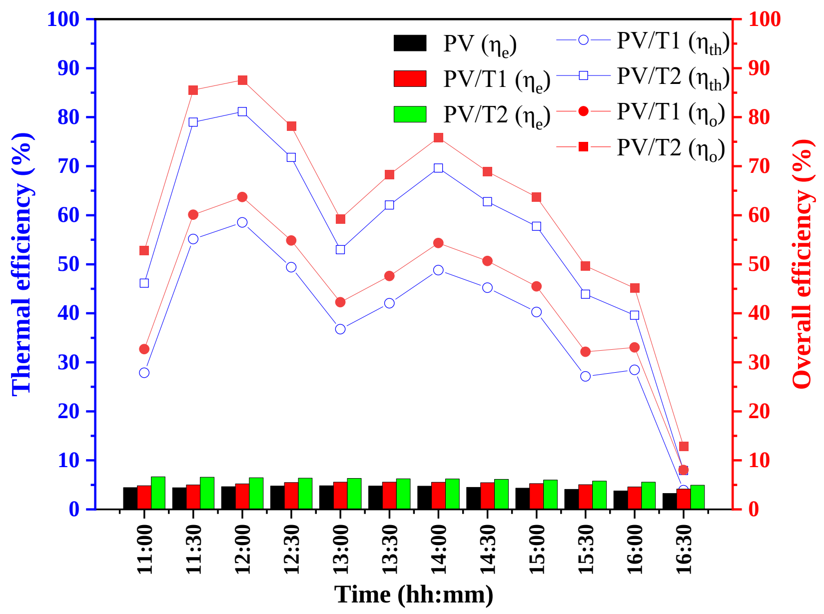
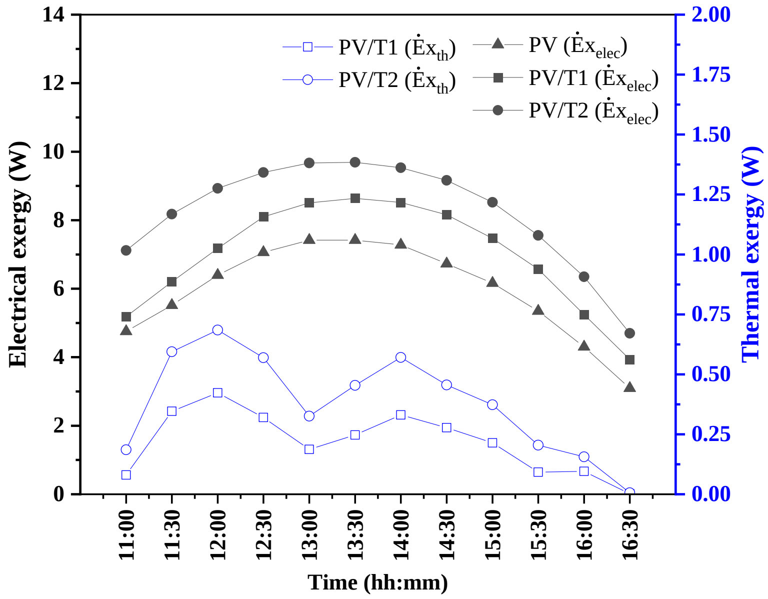
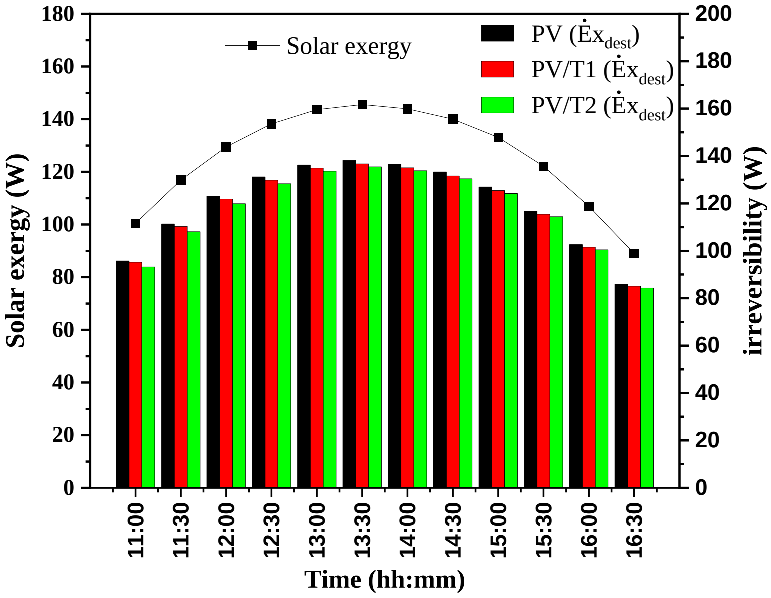


Figure 6.7. PV module and PV/T collectors' thermal and overall efficiency.

While the average values of thermal efficiency for PV/T collectors were calculated as 38.72% and 56.22% respectively. The total efficiency of PV/T1 and PV/T2 panels is the sum of the electrical and thermal efficiency for each collector since the PV panel has no thermal efficiency. According to the curves in Figure 6.7 the total efficiency over time for each of the PV/T1 and PV/T2 collectors is 43.74%, and 62.3% respectively. The reference module's overall efficiency is equal to the electrical efficiency because there is no thermal gain. Compared with PV module, the electrical efficiency of PV/T1 collector increased by 0.75% and 1.71% for PV/T2 collector. Electrical, thermal exergy, solar exergy, and irreversibility were calculated for each of PV module and PV/T collectors, shown in Figure 6.8.



(a)



(b)

Figure 6.8. Electrical, thermal exergy and irreversibility for PV module and PV/T collectors.

PV module and PV/T collectors are also analyzed depending on the second law of thermodynamics. The solar exergy during the experiment is 125.77 W. As seen in Figure 6.8, 5.96 W is converted to electrical exergy by PV module. For PV/T1 collector 6.98 W electrical exergy and 0.22 W thermal exergy are gained. 8.23 W, and 0.38 W are converted by PV/T2 collector to electrical and thermal exergy respectively. Time average value of irreversibility was approximately 119.82 W for PV, 118.58 W, and 117.16 W for PV/T1 and PV/T2, respectively. Exergy efficiencies for PV module and PV/T collectors are presented in Figure 6.9.

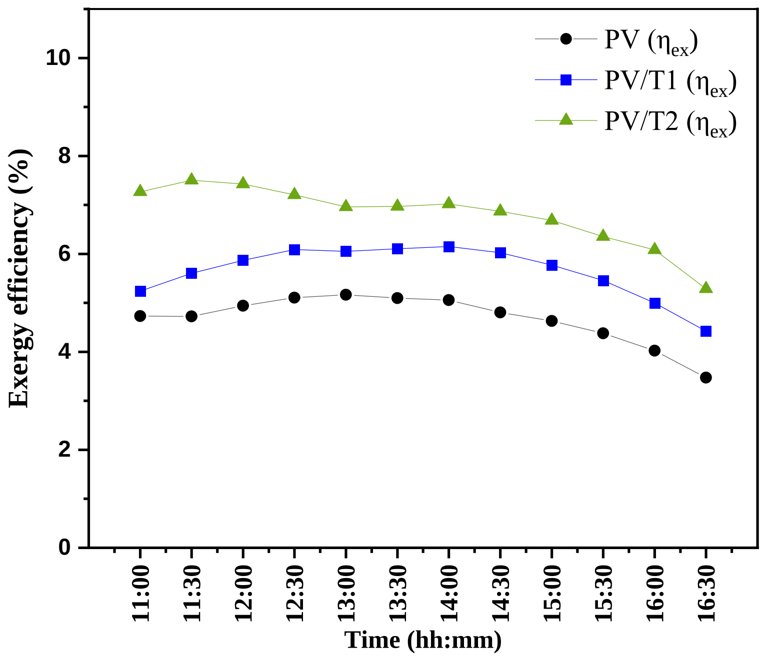


Figure 6.9. Exergy efficiencies for PV module and PV/T collectors.

PV has the lowest exergy efficiency 4.68%, and the highest destroyed exergy as seen in Fig. 6.9. The exergy efficiency for PV/T1 is about 5.65% and 6.8% for PV/T2, with an increase of 0.97% and 2.12% for PV/T1 and PV/T2 collectors respectively.

PART 7

CONCLUSION

In this experimental study, PV/T collector cooling effect on energy and exergy performance was observed by comparing PV modules data. Paraffin as PCM and steel mixture was applied on the PV modules’ back surface. The thermal load was removed from the collectors by inclined and flat heat sinks. The air around the heat sinks was deported with fan powered air flow to create active cooling. Incline and flat finned heat sink attached to collectors are called PV/T1 and PV/T2. Back side temperatures of PV/T1 and PV/T2 collectors are lowered by approximately 12.29% and 21.97% relative to PV module. This decline in temperature developed the electrical conversion performance, and the electrical efficiencies of PV/T1 and PV/T2 reached 5.12% and 6.08% compared with the PV module electrical efficiency which is 4.37%. The thermal efficiency of the collectors is 38.72% and 56.22% in the same order. The overall efficiencies of PV/T1 and PV/T2 collectors were determined as 43.74% and 62.3%. The exergy efficiency for PV module and PV/T1, PV/T2 collectors are calculated at 4.68%, 5.65% and 6.8% respectively.

PART 8

SUMMARY

In this experimental study, the behaviour of solar panels was enhanced by cooling with PCM supported by a fan for circulating air through heat sink fins. Where inclined finned heat sink was used to close the back side of one tested module named PV/T1, and PV/T2 collector used a flat finned heat sink. PV/T1 and PV/T2 collectors' collected data were compared to PV module which was used as a reference panel. Temperatures, powers, and first and second law efficiencies were calculated and compared for PV module and PV/T collectors. The results came out with an improvement in electrical energy production, and an increase in the efficiency of the PV/T collectors which the cooling system was applied on.

REFERENCES

1. Charles D. Keeling, "Industrial production of carbon dioxide from fossil fuels and limestone", ***Tellus***, 25 (2): 174–198 (2016).

2. Al-Waeli, A. H. A., Chaichan, H. A. K. M. T., and Sopian, K., "Photovoltaic / Thermal (PV / T) Systems Principles, Design, and Applications 1st ed", ***Springer Nature Switzerland AG***, 153-171 (2019).

3. Internet: REN21, "Why Is Renewable Energy Important?", **https://www.ren21.net/why-is-renewable-energy-important/** (2022).

4. Gorjian, S. and Shukla, A., "Photovoltaic Solar Energy Conversion 1st Ed", ***Academic Press***, London, 10-12,16-17 (2020).

5. McKendry, P., "Energy production from biomass (part 1): overview of biomass", ***Bioresource Technology***, 83 (1): 37–46 (2002).

6. Tong, W., "Fundamentals of wind energy", Wind Power Generation and Wind Turbine Design 1st Ed, ***WIT Press***, USA, 3–6 (2010).

7. Internet: IRENA, "Wind Energy.", **https://www.irena.org/wind** (2022).

8. Rahman, A., Farrok, O., and Haque, M. M., "Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic", ***Renewable and Sustainable Energy Reviews***, 161: 9–10 (2022).

9. Eckhart, M., El-Ashry, M., Hale, D., Hamilton, K., and Rae, P., "Global Status Report", ***REN21***, 92–97 (2020).

10. International Energy Agency, "Turkey 2021 Energy Policy Review", ***IEA***, 17–27 (2021).

11. Internet: Turkey Ministry of Energy and Natural Resources, "645646", **https://enerji.gov.tr/** (2022).

12. Kılıç, U. and Kekezoğlu, B., "A review of solar photovoltaic incentives and Policy: Selected countries and Turkey", ***Ain Shams Engineering Journal***, 13 (5): 10–11 (2022).

13. Chase, J., Hoberg, J., Houten, J. van, and Orlandi, I., "Present and Future of Solar Energy: Implications for Turkey 12-14", ***Zorlu Enerji***, Turkey, 12-14 (2015).

14. C. Julian Chen, "Physics of Solar Energy 1st Ed", ***John Wiley & Sons***, New Jersey, 1–2 (2011).

15. Duffie, J. A. and Beckman, W. A., "Solar Engineering of Thermal Processes 1st Ed", ***John Wiley & Sons, Inc***, Canada, 3-11,44 (2013).

16. Messenger, R. and Abtahi, A., "Photovoltaic Systems Engineering 4th Ed", ***CRC Press***, London, 25-27,34-35,51-53 (2017).

17. Energy Information Administration, "International Energy Outlook 2007", ***EIA***, Washington, 5 (2007).

18. Pavlovic, T., "The Sun and Photovoltaic Technologies 1st Ed", ***Springer Nature Switzerland AG***, Switzerland, 11–19 (2020).

19. Basant, A. and Tiwari;, G. N., "Building Integrated Photovoltaic Thermal Systems For Sustainable Developments 1st Ed", ***Royal Society of Chemistry***, London, 1-5,10,14 (2011).

20. Crabtree, G. and Lewis, N., "Solar energy conversion", ***Physics Today***, 60 (3): 37 (2007).

21. S.Kalaiselvam and R.Parameshwaran, "Applications of Thermal Energy Storage Systems", Thermal Energy Storage Technologies for Sustainability 1st Ed, ***Elsevier Inc.***, USA, 359–365 (2014).

22. The German Energy Societ, "Planning and Installing Photovoltiac Systems : A Guide for Installers, Architects, and Engineers 2nd Ed", ***Earthscan***, London, 85–87 (2008).

23. Shankarappa, N., Ahmed, M., Shashikiran, N., and Naganagouda, D. H., "Solar Photovoltaic Systems – Applications & Configurations", ***International Research Journal of Engineering and Technology(IRJET)***, 4 (8): 1851–1855 (2017).

24. Internet: Alternative Energy Tutorials, "Stand Alone PV System for Off-Grid PV Solar Power", **https://www.alternative-energy-tutorials.com/solar-power/stand-alone-pv-system.html** (2022).

25. Internet: Alternative Energy Tutorials, "Grid Connected PV System", **https://www.alternative-energy-tutorials.com/solar-power/grid-connected-pv-system.html** (2022).

26. Internet: Strong, S., "Building Integrated Photovoltaics (BIPV)", **https://www.wbdg.org/resources/building-integrated-photovoltaics-bipv** .

27. Alrahman, C. A., "Evaluation of a PVT Air Collector Master ", ***Dalarna University***, Sweden, 7-10 (2015).

28. Santbergen, R., Rindt, C. C. M., Zondag, H. A., and van Zolingen, R. J. C., "Detailed analysis of the energy yield of systems with covered sheet-and-tube PVT collectors", ***Solar Energy***, 84: 867–878 (2010).

29. Tonui, J. K. and Tripanagnostopoulos, Y., "Air-cooled PV/T solar collectors with low cost performance improvements", ***Solar Energy***, 81: 498–511 (2007).

30. Herez, A., El Hage, H., Lemenand, T., Ramadan, M., and Khaled, M., "Review on photovoltaic/thermal hybrid solar collectors: Classifications, applications and new systems", ***Solar Energy***, 207: 1321–1347 (2020).

31. Hasan, M. A. and Sumathy, K., "Photovoltaic thermal module concepts and their performance analysis: A review", ***Renewable and Sustainable Energy Reviews***, 14: 1845–1859 (2010).

32. Öner, İ. V., Yeşilyurt, M. K., Yilmaz, E. Ç., and Ömeroğlu, G., "Photovoltaic Thermal (PVT) Solar Panels", ***International Journal of New Technology and Research***, 2 (12): 13–16 (2016).

33. Ibrahim, A., Othman, M. Y., Ruslan, M. H., Mat, S., and Sopian, K., "Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors", ***Renewable and Sustainable Energy Reviews***, 15: 352–365 (2011).

34. Chow, T. T., "A review on photovoltaic/thermal hybrid solar technology", ***Applied Energy***, 87 (2): 366 (2010).

35. Fudholi, A., Farhana Mohd Razali, N., Ridwan, A., Yendra, R., Hartono, H., Pani Desvina, A., Khan Bin Majahar Ali, M., and Sopian, K., "Overview of Photovoltaic Thermal (PVT) Water Collector", ***International Journal of Power Electronics and Drive Systems (IJPEDS)***, 9 (4): 1892 (2018).

36. Renno, C., Landi, G., Petito, F., and Neitzert, H. C., "Influence of a degraded triple-junction solar cell on the CPV system performances", ***Energy Conversion and Management***, 160: 326–328 (2018).

37. Emam, M. and Ahmed, M., "Cooling concentrator photovoltaic systems using various configurations of phase-change material heat sinks", ***Energy Conversion and Management***, 158: 298–300 (2018).

38. Chen, H., Ji, J., Pei, G., Yang, J., and Zhang, Y., "Experimental and numerical comparative investigation on a concentrating photovoltaic system", ***Journal of Cleaner Production***, 174: 1288–1298 (2018).

39. Flitsanov, Y. and Kribus, A., "A cooler for dense-array CPV receivers based on metal foam", ***Solar Energy***, 160: 25–31 (2018).

40. Yang, F., Wang, H., Zhang, X., Tian, W., Hua, Y., and Dong, T., "Design and experimental study of a cost-effective low concentrating photovoltaic/thermal system", ***Solar Energy***, 160: 289–296 (2018).

41. Baig, H. and Mallick, T. K., "Challenges and opportunities in concentrating photovoltaic research", ***Modern Energy Review***, 3 (2): 18–20 (2011).

42. Internet: SolarFeeds Marketplace, "Concentrator Photovoltaics (CPV)", **https://solarfeeds.com/wiki/concentrator-photovoltaics/** (2022).

43. Häberle, A., "Concentrating solar technologies for industrial process heat and cooling", Concentrating Solar Power Technology 1st Ed, ***Woodhead Publishing Limited***, Germany, 608 (2012).

44. Joardder, M. U. H., Halder, P. K., Rahim, M. A., and Masud, M. H., "Solar Pyrolysis", Clean Energy for Sustainable Development 1st Ed, ***Elsevier***, Australia, 213–235 (2017).

45. Internet: Clean Energy Council 2018, "Solar Thermal", **https://www.cleanenergycouncil.org.au/resources/technologies/solar-thermal** (2022).

46. Jamil, M., M. Rizwan, and D. P. Kothari, "Grid Integration of Solar Photovoltaic Systems 1st Ed", ***CRC Press***, London, 69-72,74-78 (2018).

47. Internet: Hanania, J., Stenhouse Kailyn, and Jason, D., "Photovoltaic Effect", **https://energyeducation.ca/encyclopedia/Photovoltaic_effect#cite_ref-boyle_1-2** (2022).

48. Kaushika, N. D., Mishra, A., and Rai, A. K., "Solar Photovoltaics 1st Ed", ***Capital Publishing Company***, India, 10–11 (2018).

49. Internet: EnergySage, "Types of Solar Panels", **https://www.energysage.com** (2022).

50. Green, M. A., Hishikawa, Y., Dunlop, E. D., Levi, D. H., Hohl Ebinger, J., Yoshita, M., and Ho-Baillie, A. W. Y., "Solar cell efficiency tables (Version 53)", ***Progress in Photovoltaics: Research and Applications***, 27 (1): 3–12 (2019).

51. Internet: SOLAR, P., "Tipos de Painel Solar Fotovoltaico", **https://www.portalsolar.com.br/tipos-de-painel-solar-fotovoltaico.html** (2022).

52. Friedrich, J., von Ammon, W., and Müller, G., "Czochralski Growth of Silicon Crystals", Handbook of Crystal Growth 2nd Ed, ***Elsevier B.V.***, 45–50 (2015).

53. Mesquita, D. D. B., Silva, L. D. S., Moreira, H. S., Kitayama, M., and Villalva, M. G., "A review and analysis of technologies applied in PV modules", ***IEEE***, Gramado, Brazil, 1–6 (2019).

54. Ghazi, A. J., "Design and Evaluation of Solar Energypowerd Groundwater Pumping System for Irrigation Farm in Desert", Master Thesis, ***Çankırı Karatekin University***, Çankırı, Turkey, 13-21 (2021).

55. GORDILLO, G., "Photoluminescence and photoconductivity studies on ZnxCd1−xS thin films", ***Materials Science and Engineering***, 40 (1): 1–46 (2003).

56. Internet: 8MSolar, "The Three Types of Solar Panels", **https://www.8msolar.com/types-of-solar-panels** (2022).

57. Xiao, W., "Photovoltaic Power System : Modeling, Design, and Control", Photovoltaic Power System 1st Ed, ***John Wiley & Sons Ltd***, India, 2-4,7-8 (2017).

58. Qazi, S., "Standalone Photovoltaic (PV) Systems for Disaster Relief and Remote Areas 1st Ed", ***Elsevier***, United States, 47–48 (2017).

59. G. N. Tiwari and Dubey, S., "Fundamentals of Photovoltaic Modules and Their Applications 1st Ed", ***Royal Society of Chemistry***, New Delhi, 103–113 (2010).

60. Pode, R. and Boucar, D., "Solar Lighting 1st Ed", ***Springer-Verlag London Limited***, New York, 26-30,36-38 (2011).

61. Yuanyuan, W., "Comparison of different commercial solar photovoltaic modules", Master Thesis, ***Tampere University of Technology (TUT)***, Finland, 5 (2016).

62. Pearsall, N., "The Performance of Photovoltaic (PV) Systems 1st Ed", ***Woodhead Publishing***, United States, 6-11,23-25 (2017).

63. Mayfield, R., "Photovoltaic Design & Installation For Dummies 1st Ed", ***Wiley Publishing, Inc***, Canada, 109–120 (2010).

64. Mishra, R. K. and Tiwari, G. N., "Energy and exergy analysis of hybrid photovoltaic thermal water collector for constant collection temperature mode", ***Solar Energy***, 90: 58–67 (2013).

65. Dubey, S., Solanki, S. C., and Tiwari, A., "Energy and exergy analysis of PV / T air collectors connected in series", ***Energy and Buildings***, 41 (8): 863–870 (2009).

66. Tiwari, G. N., Tiwari, A., and Shyam, "Handbook of Solar Energy 1st Ed", ***Springer Science+Business Media Singapore***, USA, 27–28 (2016).

67. Internet: Solar Light Company, I., "Pyranometer", **https://solarlight.com/wp-content/uploads/PMA2145-879x400.jpg** (2022).

68. Internet: Magesolar, "Solar Meter", **https://magesolar.com** (2022).

69. Misiopecki, C., Gustavsen, A., and Time, B., "Cooling of PV panels by natural convection", ***SINTEF Academic Press Cezary***, Trondheim, 1-22 (2012).

70. Mazón-Hernández, R., García-Cascales, J. R., Vera-García, F., Káiser, A. S., and Zamora, B., "Improving the electrical parameters of a photovoltaic panel by means of an induced or forced air stream", ***International Journal of Photoenergy***, 2013: 1–10 (2013).

71. Sultan, S. M., Tso, C. P., and Efzan, M. N. E., "A new method for reducing the performance evaluation cost of the photovoltaic module cooling techniques using the photovoltaic efficiency difference factor", ***Case Studies in Thermal Engineering***, 21: 1–9 (2020).

72. Arifin, Z., Tjahjana, D. D. D. P., Hadi, S., Rachmanto, R. A., Setyohandoko, G., and Sutanto, B., "Numerical and experimental investigation of air cooling for photovoltaic panels using aluminum heat sinks", ***International Journal of Photoenergy***, 2020: 1–10 (2020).

73. Kumar, R., Praveen, P., Gupta, S., Saikiran, J., and Bharj, R. S., "Performance evaluation of photovoltaic module integrated with phase change material-filled container with external fins for extremely hot climates", ***Journal of Energy Storage,*** 32: 1–12 (2020).

74. Sharma, S., Tahir, A., Reddy, K. S., and Tapas K. Mallick, "Solar Energy Materials & Solar Cells Performance enhancement of a Building-Integrated Concentrating Photovoltaic system using phase change material", ***Solar Energy Materials and Solar Cells***, 149: 29–39 (2016).

75. Mehling, H. and Cabeza, L. F., "Phase Cgange Marerials and Their Basic Properties", Thermal Energy Storage for Sustainable Energy Consumption 1st Ed, ***Springer***, 257–277 (2007).

76. Chandel, S. S. and Agarwal, T., "Review of cooling techniques using phase change materials for enhancing efficiency of photovoltaic power systems", ***Renewable and Sustainable Energy Reviews***, 73: 1342–1351 (2017).

77. Bahaidarah, H., Subhan, A., Gandhidasan, P., and Rehman, S., "Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions", ***Energy***, 59: 445–453 (2013).

78. Krauter, S., "Increased electrical yield via water flow over the front of photovoltaic panels", ***Solar Energy Materials & Solar Cells***, 82: 131–137 (2004).

79. Gotmare, J. A., Borkar, D. S., and Hatwar, P. R., "Enhancement the Performance of PV Panel by Using Fins as Heat Sink", ***Engineering and Technology Journal***, 03 (02): 447–454 (2015).

80. Bayrak, F., Oztop, H. F., and Selimefendigil, F., "Effects of different fin parameters on temperature and efficiency for cooling of photovoltaic panels under natural convection", ***Solar Energy***, 188: 484–494 (2019).

81. Selimefendigil, F., Bayrak, F., and Oztop, H. F., "Experimental analysis and dynamic modeling of a photovoltaic module with porous fins", ***Renewable Energy***, 125: 193–205 (2018).

82. El Mays, A., Ammar, R., Hawa, M., Akroush, M. A., Hachem, F., Khaled, M., and Ramadan, M., "Improving Photovoltaic Panel Using Finned Plate of Aluminum", ***Energy Procedia***, 119: 812–817 (2017).

83. Thongtha, A., Chan, H. Y., and Luangjok, P., "Influence of phase change material application on photovoltaic panel performance", ***Key Engineering Materials***, 730: 563–568 (2017).

84. Su, D., Jia, Y., Alva, G., Liu, L., and Fang, G., "Comparative analyses on dynamic performances of photovoltaic–thermal solar collectors integrated with phase change materials", ***Energy Conversion and Management***, 131: 79–89 (2017).

85. Sathe, T. M. and Dhoble, A. S., "Thermal management of low concentrated photovoltaic systems using extended surfaces in phase change materials", ***Journal of Renewable and Sustainable Energy***, 10 (4): 1–19 (2018).

86. Rajvikram, M., Leoponraj, S., Ramkumar, S., Akshaya, H., and Dhee, A., "Experimental investigation on the abasement of operating temperature in solar photovoltaic panel using PCM and aluminium", ***Solar Energy***, 188: 327–338 (2019).

87. Sardarabadi, M., Passandideh-Fard, M., Maghrebi, M.-J., Mohsen, and Mohsen Ghazikhani, "Experimental study of using both ZnO/ water nanofluid and phase change material (PCM) in photovoltaic thermal systems", ***Solar Energy Materials & Solar Cells***, 161: 62–69 (2017).

88. Soliman, A. M. A., Hassan, H., and Ookawara, S., "An experimental study of the performance of the solar cell with heat sink cooling system", ***Energy Procedia***, 162: 127–135 (2019).

89. Michelia, L., Reddy, K. S., and Mallicka, T. K., "Plate micro-fins in natural convection: an opportunity for passiveconcentrating photovoltaic cooling", ***Energy Procedia***, 82: 301–308 (2015).

90. Popovici, C. G., Hudişteanu, S. V., Mateescu, T. D., and Cherecheș, N.-C., "Efficiency improvement of photovoltaic panels by using air cooled heat sinks", ***Energy Procedia***, 85: 425–432 (2016).

91. Soliman, A. M. A. and Hassan, H., "3D study on the performance of cooling technique composed of heat spreader and microchannels for cooling the solar cells", ***Energy Conversion and Management***, 170: 1–18 (2018).

92. Rajput, U. J. and Yang, J., "Comparison of heat sink and water type PV/T collector for polycrystalline photovoltaic panel cooling", ***Renewable Energy***, 116: 179–491 (2018).

93. Alzaabi, A. A., Badawiyeh, N. K., Hantoush, H. O., and Hamid, A. K., "Electrical/thermal performance of hybrid PV/T system in Sharjah, UAE", ***International Journal of Smart Grid and Clean Energy***, 3 (4): 385–389 (2014).

94. Mousavi Baygi, S. R. and Sadrameli, S. M., "Thermal Management of Photovoltaic Solar Cells Using Polyethylene Glycol1000 (PEG1000) as a Phase Change Material", ***Thermal Science and Engineering Progress***, 5: 405–411 (2018).

95. Li, Z., Ma, T., Zhao, J., Song, A., and Cheng, Y., "Experimental study and performance analysis on solar photovoltaic panel integrated with phase change material", ***Energy***, 178: 471–486 (2019).

96. Abdelrahman, H. E., Wahba, M. ., Refaey, H. ., Moawad, M., and Berbish, N. S., "Performance enhancement of photovoltaic cells by changing configuration and using PCM (RT35HC) with nanoparticles Al2O3", ***Solar Energy***, 177: 665–671 (2019).

97. Sarikarin, T., Wongwuttanasatian, T., and Suksri, A., "Cooling enhancement of photovoltaic cell via the use of phase change materials in a different designed container shape", ***Earth and Environmental Science PAPER***, 257: 1–9 (2019).

98. Hachem, F., Abdulhay, B., Ramadan, M., El, H., Gad, M., Rab, E., and Khaled, M., "Improving the performance of photovoltaic cells using pure and combined phase change materials e Experiments and transient energy balance", ***Renewable Energy***, 107: 567–575 (2017).

99. Hasan, A., Sarwar, J., Alnoman, H., and Abdelbaqi, S., "Yearly energy performance of a photovoltaic-phase change material (PV-PCM) system in hot climate", ***Solar Energy***, 146: 417–429 (2017).

100. Nada, S. A., El-Nagar, D. H., and Hussein, H. M. S., "Improving the thermal regulation and efficiency enhancement of PCM- Integrated PV modules using nano particles", ***Energy Conversion and Management***, 166: 735–743 (2018).

101. Diniz, F. L. J., Vital, C. V. P., and Gómez-Malagón, L. A., "Parametric analysis of energy and exergy efficiencies of a hybrid PV/T system containing metallic nanofluids", ***Renewable Energy***, 186: 51–65 (2022).

102. Mahdavi, S., Sarhaddi, F., and Hedayatizadeh, M., "Energy/exergy based-evaluation of heating/cooling potential of PV/T and earth-air heat exchanger integration into a solar greenhouse", ***Applied Thermal Engineering***, 149: 996–1007 (2019).

103. Manjunath, C., Reddy, J., Reddy, K. S. R., Kumar, I. R. G., and Sanketh, S., "Energy, exergy performance and analysis of 50w solar photovoltaic module", ***Materials Today: Proceedings***, 54: 531–536 (2022).

104. Yousef, M. S., Sharaf, M., and Huzayyin, A. S., "Energy, exergy, economic, and enviroeconomic assessment of a photovoltaic module incorporated with a paraffin-metal foam composite: An experimental study", ***Energy***, 238: 121807 (2022).

105. Adun, H., Adedeji, M., Ruwa, T., Senol, M., Kavaz, D., and Dagbasi, M., "Energy, exergy, economic, environmental (4E) approach to assessing the performance of a photovoltaic-thermal system using a novel ternary nanofluid", ***Sustainable Energy Technologies and Assessments***, 50: 101804 (2022).

RESUME

Ahmad AL HARIRI was born in Syria and studied primary and secondary schools in Syria. He graduated from Damascus University as a mechanical engineer in 2010. He is currently studying for M.Sc in Energy Systems Engineering at Karabuk University and is still.