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Deanship of Graduate Studies and Scientific Research

Master Program of Renewable Energy and Sustainability

Experimental study of design a hybrid photovoltaic thermal collector (PVT -collector) for a domestic use.

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Thesis submitted in partial fulfillment of requirements of the degree

Master of Science in Renewable Energy & Sustainability

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The undersigned hereby certify that they have read, examined and recommended to the Deanship of Graduate Studies and Scientific Research at Palestine Polytechnic University and the Faculty of Science at Al-Qdus University the approval of a thesis entitled:

Experimental study of design a hybrid photovoltaic thermal collector (PVT -collector) for a domestic use.

Submitted by

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In partial fulfillment of the requirements for the degree of Master in Renewable Energy & Sustainability.

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ABSTRACT

One of the most important modern technologies in the field of thermal and electrical energy production for various applications such as, domestic applications, is the PVT system. New PVT system has a significant potential for preheating water and producing electricity at the same time and in different seasons. Through this system, the collector can be used to obtain two forms of solar energy (thermal and electrical), without separating them and utilizing the same area. In recent years, various research have been conducted to design different collectors to improve electrical and thermal efficiency. The focus of this research is to evaluate the electrical and thermal performance of new PVT collector design, and compare it with conventional PV panel and thermal collector. The performance evaluation is an important step to optimize the design, and to give right solution for problems that may be unclear and negatively affect the performance of the collector. The evaluation process involves monitoring and setting up several design parameters such as, electric and thermal power production for the PVT collector, conventional PV panel and thermal collector. The effect of weather conditions on the electrical and thermal efficiency is also considered in addition to difference in temperature between the inlet and outlet water in the collectors.

Part of our contribution, the PVT collector which consists of a photovoltaic panel is installed on a thermal collector. The thermal panel contains parallel pipes through which the water passes. The pipes are surrounded by the paraffin wax. A set of thermal sensors have been installed in paraffin wax, behind the PV panel which was combined with thermal collector, and behind the conventional PV panel. Other sensors have been selected and placed at the input and at the outlet of water for PVT collector and conventional thermal collector. The electric sides of the photovoltaic panels were also connected to the measuring devices to measure the generated voltage and current.

The experimental prototype which consists of design the PVT collector and conventional thermal collector, and conventional PV panel were oriented toward the south on the top roof of building in coordinates (31°26 N, 35°05 E), Palestine, from February till May 2019.

Using different tools for measurement such as voltmeter and ammeter, thermocouple and thermometer devices, solar radiation and wind collected by Palestine Polytechnic University (PPU) renewable lab. The Results show that the thermal efficiency of the PVT collectors and the conventional thermal collector is very close to each other. The electrical efficiency of the PV_{PVT} and PV_{CO} is close to each other 8%, but it starts with a relative difference when the solar radiation increases dramatically, where the photovoltaic cells being heated in PV_{PVT} more than in PV_{CO}. The features of the integrated PVT collector for thermal and electric energy can be obtained at the same time. Where the electrical energy that produced can be used to operate electric heaters that heat up the water in the tank as needed, especially in winter.

دراسة تجريبية لتصميم مجمع حراري كهروضوئي هجين (PVT) للاستخدام المنزلي.

اعداد : هيثم يوسف "حمد عواد"

ملخص

في هذه الرسالة تم تقديم تصميم لمجمع حراري كهروضوئي، يتم من خلاله انتاج طاقة حرارية واخرى كهربائية، يمكن الاستفادة منها في تسخين الماء للتطبيقات التي تحتاج الى المياه الساخنة بشكل عام و للاستخدامات المنزلية بشكل خاص. التصميم المقترح هو عبارة عن لوح يجمع خصائص اللوح الحراري اضافة الى اللوح الكهروضوئي ، تم دمجهما معا ليصبحا لوحا واحدا يتم من خلاله تسخين الماء المار في الانابيب داخله، اضافة لتوليد الكهرباء التي يمكن استخدامها لاحقا لتشغيل مسخنات حرارية تعمل على رفع درجة حرارة الماء في الخزان الموصول مع اللوح الى الحد المطلوب. هذا التصميم قُدم ليكون حلا عمليا يتم من خلاله استغلال نفس مساحة سطح البناء المحدودة لبناء نظام بتكلفة اقل من بناء نظامين منفصلين، واحد حراري واخر كهربائي. خلال هذه الدراسة تم عمل مقارنات تحليلية بين التصميم الجديد مع لوح شمسي مستقل واخر كهروضوئي منفصل، من خلال البيانات التي تم جمعها من النظام.

DECLARATION

I declare that the Master Thesis entitled” Experimental study of design hybrid photovoltaic thermal collector (PVT -collector) for a domestic use” is my own original work, and herby certify that unless stated, all work contained within this thesis is my own independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

Student Name: Haytham Yousef “HamedAwwad”

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DEDICATION

My leader ... Prophet Mohammad

To the beloved martyrs of Palestine...

To our prisoners ... the torch of light...

To my dear parents...

To my wife and dear sons...

To the supervisors of my dear thesis... Dr. Maher Maghalseh, and Dr. Hassan Sawalha.

To family and friends...

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LIST OF ABBREVIATIONS

IEA	Energy International Administrator
PV	Photovoltaic panel
PVT	Photovoltaic thermal collector
PVCO	Conventional photovoltaic panel
PVPVT	Photovoltaic panel combined with thermal collector
PCM	Phase change material
DC	Direct current
PTC	Parabolic Trough Collector
LFR	Linear Fresnel Reflector
FPC	Flat plate collector
ETC	Evacuated tube collector
CPC	Compound parabolic collector
CTC	Cylindrical trough collector
PDR	Parabolic dish reflector
HFC	Heliostat field collector
Si	Silicon
V_{oc}	Open circuit voltage
I_{sc}	Short circuit current
CPV	Concentrating photovoltaic
STC	Standard test conditions
η_{th}	Thermal efficiency
η_{el}	Electrical efficiency
PPVT	Maximum power from photovoltaic thermal collector
PPV	Maximum power from photovoltaic panel
FF	Fill factor
P	Power
V	Voltage
MPP	Maximum power point
G	Solar radiation
NOCT	Normal operating cell temperature
T_C	Temperature of photovoltaic panel
T_a	Ambient air temperature
T_{up}	Temperature upside
T_{do}	Temperature down side
T_{re}	Reduced temperature
T_i	Inlet temperature
T_o	Outlet temperature

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Chapter 1.

1. Introduction

1.1 Background:

Nowadays, the need of renewable energy comes from many problems that the world have been affected from, such as global warming and environmental pollution. These problems are compounded by the high demand of the power, mostly being supplied by burning fossil fuels and other natural materials [1]. Energy International Administrator (IEA) organization's data in 2017 indicated that the primary source of energy production was consisted of coal with 27.3% ,natural gas 26.8% ,nuclear 17.7%, and the renewable energy (solar, wind, geothermal, other) with 9.6%. In 2008 IEA data shows dependence of coal of 36%, natural gas 22%, nuclear 21% and renewable energy of 2.5%, this indicates the importance of renewable energy source and the future trend by noting the decrease in non-renewable energy sources demands and a higher demands for renewable energy sources.

There are different types of renewable energy sources that can be used, like wind, geothermal, biofuels, solar energy, and others. But the use of one or more of these types depend on some factors, some of them are the cost-effective, environmental impact, location for installation, and the amount of power which can be obtained from it by using some applications. However, the most important form of renewable energy sources that the world is mostly focused on is solar energy. Solar energy is a clean, safe, and without a doubt renewable. Also it's important to notice that it can benefit from the two main forms of energy, namely thermal energy and photovoltaic energy without any environmental pollution [2-7].

To take advantage of the two types of solar energy in its applications, and by depending on the methods of work, different types of devices could be used. First, for the thermal solar energy, different types of solar collectors which are considered as a heat exchanger can be used for absorbing the incoming solar radiation and converting it to heat energy. The obtained energy could be used to heat fluids -such as: water and oil-. Also for space heating. Collectors' types are used in domestics, industrial and other huge applications. These types includes: flat plate, evacuated tube, parabolic trough or dish, and others. For photovoltaic energy, a photovoltaic cell or panel are used to convert the sunlight to electricity, using the photoelectric effects [1, 6, and 7].

For the past few decades, there have been a high increase in the solar market, in thermal or photovoltaic needs. We can see developments in this field concentrated to increasing the efficiency of various types of solar collectors and PV-panels; photovoltaic thermal (PVT) collectors are one such being developed [2]. The PVT collector is a device that integrates between the solar thermal collector and the PV- panel to generate the thermal and electric energy at the same time [1].

In the different research [1] we can see that the use of building integrated PVT is more efficient than the use of separate systems of PV-panels and the thermal collectors. In this research, the experimental work is to design a new type of PVT-collector by integrating the PV-panel with the thermal collector, and use special material between them to work as thermal storage, and by this new design we can meet the domestic demand per/home (4-7 persons in a home) in an efficient way.

1.2 Problem Statement:

The ability of the PVT-collector to absorb the two types of solar energy (thermal and photo), and convert it in the two forms (heat and electricity), to be used at the same time with high efficiency, it's the main key of the PVT-collector performance. The total efficiency of PVT-collector defined as, the sum of thermal and electric efficiency [1].

One of main problems with the thermal solar collector is, -in winter - there is not enough heat to heat the water to supply the domestic application. Our experimental work is to design a new type of collector, which is a PVT-collector that is used to solve this problem. By using the PVT-collector we can take advantage of two types of solar energy, the thermal and electrical to generate heat and electricity at the same time, which can be used to heat water for domestic need.

1.3 Aim and Objectives:

To achieve the objective of this project, the following goals must be completed:

- Study and implementation of thermal behavior and characteristic.
- Study and implementation of the electric PV- characteristic combined with PVT-collector.
- Design and implementation a PVT-collector for domestic application.

- Study and implementation of using PCM-material on both thermal and electric characteristic of PVT-collector.

1.4 Methodology:

In order to analyze the performance of the new design of PVT-collector (thermal and electricity generation), we designed a system at the same location and direction, that consists of thermal collectors connected with storage tank as alone, a new PVT-collector connected with another storage tank, and PV-panel (with same properties of the PV- panel which is used in PVT-collector) installed alone in a place adjacent to the other systems.

Our methodology in these is:

- Conduct an experimental work for the three different modules. The first one is PV-panel without thermal collector, the second is thermal collector without PV, and the third is the PV with thermal collector (PVT).
- Data collecting and analysis for the potential of weather conditions, like solar radiation, wind speed.
- Experimentally, study the thermal and electrical efficiencies of PVT system and compare it with the thermal collector and the PV-panel which is separate.

1.5 Thesis Structure:

The thesis consists of five chapters, **chapter 1** starts with a general introduction about renewable energy then shows the objective and the methodology, at the end with thesis structure.

Chapter 2 presents a review of the PVT-collector. The main concept of its design, some PVT-collector design, and its uses, compare between different types of PVT-collector.

Chapter 3 presents the work of design a new PVT-collector. The materials and components that it was used.

Chapter 4 shows the data collected for the different systems. Compared between these systems by depending on data collected.

Chapter 5 gives the main conclusion from this study. Submit a Suggestion for future work to develop the design.

CHAPTER 2

2. Literature Review and Background

2. 1 Introduction:

One of the main sources of renewable energy is solar energy, which it could be benefits from in two ways. First, is the thermal energy, where there are many collectors' types that were designed and manufactured in the world to collect the thermal energy in the best way, and then convert it to any form of energy, like heating the water, or for heating or cooling an area, one of this type is flat plat collector. The second one is photoelectric energy, where they use a photovoltaic cell to convert the sunlight to direct power (DC power). To obtain energy values that suit the needs of different employment, they are connected in series and parallel to get a PV-module. These modules are connected to generate the power needed. In recent decades there are new designs that combine the thermal collector and the PV-panel which is PVT-collectors. From these collectors, we get the two types of solar energy at the same time [1-3]. Figure (2.1) shows the schematic different advantages of the solar energy

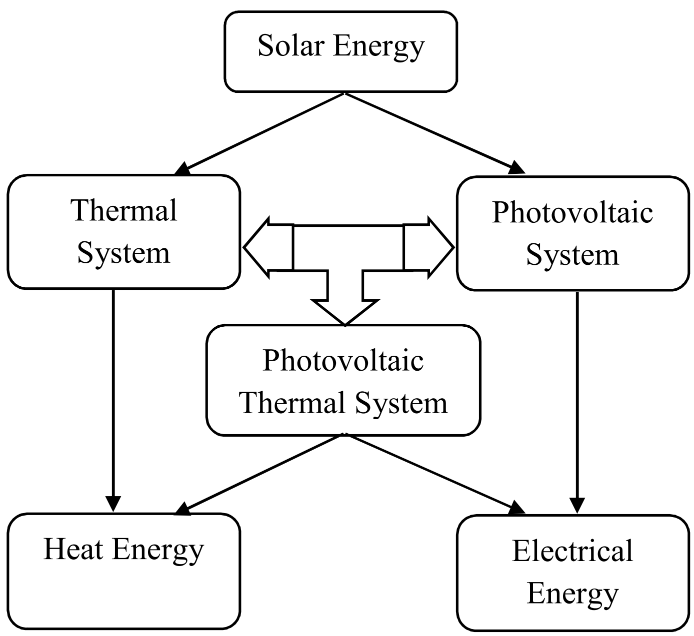

Figure 2. 1: Schematic design shows different advantages of the solar energy

2.2 Solar Thermal Collectors:

Solar Thermal Collectors are a heat exchanger devices, which absorbs the solar energy and transmits it to another medium and converts it into heat, then transfers this heat to a working fluid like water, air or oil. These collectors are divided into two types: the concentrating and the non-concentrating collector. The main difference between them is: with non-concentrating collectors, all areas of the collector intercepts the solar radiation and absorbs it; with concentrating collector, it has a reflecting surface that absorbs and reflects the solar radiation in a smaller receiving area Installed in an area to receive all reflected radiation [6, 7].

The flat plate collector is one of the non-concentrating collector type, where it's simpler in mechanical design than the concentrating collector. This type of collectors is designed for operation at low or medium temperature to supply domestic and industrial purposes. Also needed is a stream liquid or gas with a temperature range between (60 – 100 ^{O}C). The flat plate collector has its different advantages such as, it needs a little of maintenance, it uses two main types of sun's radiation beam and diffuse and not require sun tracking, and it placed on the top of building [6, 20]. A flat plate collector consists of metal box covered by the glazing (glass or plastic). The pipes inside which the heating fluid pass through, covered by a black absorber plate [15].

Another type of non-concentrating collector is the evacuated tube. This type of collectors is one of the most advanced types, which is used in applications that need high temperatures (more than 80 ^{o} C), higher than the temperature obtained through the flat plate collector. The principle of its work based on the vacuum, in this technique, even if the weather conditions are relatively bad it works. Unlike flat plat which is at the same weather conditions does not work well [6, 7].

To provide energy at high temperature, the flat plate collector and evacuated tube is not the right choice. You need other types of collectors which is the concentrating type. With these types of collectors, the solar radiation is optically concentrated by using a reflector on the absorber to be transferred into heat. The design of this collector consists of a receiver Installed in a place to receive all sun radiation that is reflected from the reflector. From this design, we can increase the energy temperature delivered, by decreasing the area which the heat losses occur. There are different designs and types of the concentrating collectors, where the choice one of them depend on some factor like sun tracking, temperature need, space, and other. The Parabolic Trough Collector (PTC) is one of these types which is has a receiver pipe installed above parabolic reflector, with one axis sun radiation tracking. It successfully supplying thermal energy up to (250 ° C). Other type is Linear Fresnel Reflector (LFR), here, using flat mirrors which is cheaper than those that form parabolic, installed close to the ground without need much structural requirements, focus the solar radiation on the receiver installed at the top of tower or to the receiver pipe which installed above the mirrors. in central receiver system, the receiver install on the top of a tower and uses the heliostat mirror with two-axis tracking to reflect the solar radiation in focal point. It use to have temperature up to (2000 ° C). [6, 7, 15, 20, 31].

Summary:

Concerning any of these collector types, there are some factors we must know about: the temperature needed for the utilization, amount of free space, cost, and others. Table (2.1) shows the difference between these types of collectors from the absorber type and concentration ratio and the temperature range. Table (2.2) shows the thermal efficiency for these solar collectors.

Table 2. 1: different types of solar thermal collector [7]

Motion	**Collector type**	**Absorber type**	**Concentration ratio**	**Indicative temperature range (ºC)**
Stationary	Flat plate collector (FPC)	Flat	1	30-80
	Evacuated tube collector (ETC)	Flat	1	50-200
	Compound parabolic collector (CPC)	Tubular	1-5	60-240
Single-axis tracking	Linear Fresnel reflector (LFR)	Tubular	10-40	60-250
	Parabolic trough collector (PTC)	Tubular	15-45	60-300
	Cylindrical trough collector (CTC)	Tubular	10-50	60-300

Two-axes tracking	Parabolic dish reflector (PDR)	Point	100-1000	100-500
	Heliostat field collector (HFC)	Point	100-1500	150-2000

Table 2. 2: Thermal efficiency of different types of solar thermal collectors [20]

Category	Example	Temperature range, °C	Efficiency, %
No concentration	Flat-plate	up to 75	30 – 50
	Evacuated tube	up to 200	
Medium concentration	Parabolic cylinder	150 - 500	50 – 70
High concentration	Parabodial dish	1500 and more	60 - 75

2.3 Solar Photovoltaic:

Solar Photovoltaic technology has a shorter history than the solar thermal collector. The first beginnings of the discovery of photovoltaic cells date is back to 1839, while the actual work to build the first cell it wasn't until 40 years later, by two scientists, they were designing the first solar cell of Selenium with an efficiency of (1-2%). From that day the discovery of materials suitable for the manufacture of photovoltaic cells is still progress. In 1940s and 1950s the Polish scientist Czochralski developed a theory based on silicon crystals in the photovoltaic industry, which is still an important foundation in building this system to this day. Due to the high cost of producing these photovoltaic cells, their use was limited to space-related applications. However, when the energy crisis occurred in the 1970s, research into the development of these cells was intensified until it became available in applications such as calculators, water pumps in remote areas, Which helped to lower the cost, but the big shift was in the 1990s, where there was a clear and significant reduction in the cost price, which opened the way for the spread of these PV systems [7, 13, 32].

The photovoltaic cell is made of semiconductor material, like silicon (Si) compound of cadmium sulphide (Cds), gallium arsenide (GaAS), copper sulphide (Cu_2S). The principle of it, is to convert the sun's light to DC current. The efficiency of this cell is between 6-18%, where 82% of the incoming solar energy may be reflected or absorbed as heat. This depends on the solar cell type used. The heat may reduce the efficiency of the cell approximately by (0.5%/C) for typical silicon based the PV-cells. Equation (1) and (2) show that temperature effect on the V_{oc} more than I_{sc} [7, 12, 13, and 19].

$$I_d = I_o(e^{\left(\frac{qV_d}{KT}\right)} - 1) \qquad (1)$$

$$\frac{dV_d}{dT} = -\frac{V_{go} - V_d + \gamma(\frac{KT}{q})}{T} \qquad (2)$$

- I_d: the diode current (A).
- I_O: the reverse saturation current (A).
- V_d: the voltage across the diode terminal from the p-side to the n-side (V).
- K: Boltzmann's constant (1.381×10^{-23} J/K).
- T: junction temperature (K).
- q: the electron charge (1.602×10^{-19} C).

The photoelectric cell is manufactured on several categories which depend on the material used. The first one is a solar cell from silicon. This type is divided into three main type: a single crystalline silicon, this type has high efficiency performance, where the efficiency of a single crystalline silicon = 24.7%, and the commercial Si solar cell =18%. But it has high cost. The second, Polycrystalline silicon, it has small grains of silicon, affecting the efficiency of cell, less than the cell made of pure silicon. This efficiency is between (10-14%). but there are several advantages of Polycrystalline cell, it has low cost, is stronger and can be cut into another small thickness. Amorphous silicon is the third type, it's a non-crystalline form of silicon, where the silicon atoms are in a disordered structure. It was discovered in 1974, and used to produce the first thin film PV-module. It has high absorptivity than that of single-crystal silicon it's about 40 times higher. The second type of solar cell is III-V group solar cells, It is divided into two types: 1- Gallium arsenide (GaAs), which is made of compound semiconductor elements: gallium (Ga) and arsenic (As). 2- Indium phosphide (INP). The third type of solar cell is thin films solar cells, is manufactured by deposit a thin layer of PV semiconductor materials on low-cost supporting layer such as glass, plastic foil or metal. The conversion efficiency of this type is lower than in other types. It has a low weight which makes it easy to install [6, 7].

PV-cells are connected in series and parallel to produce PV-panel. The PV-panels are also connected together in series a parallel to produce PV-array. By this, we can built PV power plants to meet the residential and industrial needs of energy. However, many circumstances can affect the amount of power a PV system can generate; for instance, power station capacity, the site, the technology used in a PV system (a type of cell, and its efficiency), the weather condition, and other [1, 7,13].

Summary:

There are several types of semiconductor materials which have been used to make the different varieties of solar cells, to convert the solar energy to electricity. The main requirement of a material to be suitable for the solar cell called a band gab. For any material used it should be between (1.1-1.7 eV) [6]. Table (2.3) shows the different value of a band gab and cut off wave length for different semiconductor materials.

Table 2. 3: Band Gap and Cut-off Wavelength Above which electron excitation doesn't occur. [32]

Quantity	Si	GaAs	CdTe	InP
Band gap (eV)	1.12	1.42	1.5	1.35
Cut-off wavelength (μm)	1.11	0.87	0.83	0.92

2.4 Photovoltaic thermal collector (PVT):

The Photovoltaic thermal collector (PVT) is a hybrid PV system that is combined of PV-module and thermal module in the same collector, where it can convert the two types of solar energy (thermal and light) to produce heat and electricity energy at the same time [1-6]. There is a large amount of research which was conducted in PVT system to give a good design that gives a high electric and thermal efficiency. The beginning is in the mid of 1976, Wolf M. analyzed the performance of silicon solar array that is mounted inside a flat plate collector, and use a lead-acid battery to store the electric power. He concluded that, this type of technology is feasible, and it is cost effective. Subsequently, in 1978, Kern and Russell give a basic design of cooling the solar cell by using water and air. In 1979, Florschuetz give anew design that combined flat plate collector and solar cell, to use it in cooling the solar cell for increasing electric efficiency. The numerical methods that predicting the performance of the PVT flat collector water or air, are presented in 1981. And in 1982, the theoretical model of the combined PVT collector was developed by Hendrie. A PVT-system that based on natural convection of water was studied and experimented on it in 1994. And in 1995, Garg and Agarwal give a study of a forced circulation PVT-system and develop a mathematical model for it. Subsequently, the development of the PVT-collector is still growing up to nowadays. And this depends on modifications and changes in several factors, such the types of solar cells used and its efficiency, use glazing or not, the mass flow rate of fluid used, the system dimensions, weather condition, and application type. Using a PVT-collector help to take advantages in many features as [1, 6, 8, 10-12, and 19]:

- if roof area is limited we can use the same collector area to produce electric and thermal energy from the sun's energy at the same time and with high overall efficiency.
- Recover the heat energy lost which is produced in solar cell after absorbing the solar radiation.
- Hybrid PVT-collector increases the electric efficiency of the solar cell by cooling it. Where the efficiency of solar cell decreases by (0.4 - 0.5%/C).

There are many of PVT-collectors was designed, which give high results of electrical and thermal energy. One of the main factors that affects the PVT-collector efficiency is the fluid type used and concentration. PVT-collectors classified into three types: liquid PVT type, air PVT, and PVT concentrator type. The PVT-collector that uses water is more efficient than air PVT-collector. Using the air to reach the electrical efficiency of (10 - 13%), and the thermal efficiency reaches (40 - 55%). While the use of water increases the electrical efficiency of PV panels from (15 - 20%), in addition to obtaining thermal efficiency of (60 - 70%) to heat water and using it in household applications. PVT concentrating type operates at higher temperature than those in flat plate, where the basic principle is to use the concentrating reflector to generate electricity from the solar cell and then collecting the rejected heat from the concentrating photovoltaic (CPV) to generate heat. The research in the PVT concentrating type continues to develop this type and increases the thermal and electric generation [1, 2, 5, and 6].

Summary:

Different designs of PVT-collectors vary from each other by different factors like: the type of the used solar cell, the weather conditions, the used glass or its absence in the plates or the used fluid. Table (2.5) show the summary of PVT collectors' designs with the calculations of thermal and electrical efficiency.

Table 2. 4: Summary of PVT collector

Ref. #	Type of PV/T technology	thermal efficiency	PV Efficiency	Applications
1	air	50%	10.6%	A numerical and experimental study for solar concentrating PV system (CPVT) and compare it with flat plate-PVT (FPVT). its indicated that the heat losses is lower in (CPVT) than (FPVT)
	air	23%	15%	Experimental study of using this system to heat recovery ventilation for preheating the outside air intake.
	water	55–62%	11.4%	conducted study to investigate the use of single glazing sheet multi crystal photovoltaic (PV) module, with a flat plate collector, for BIPVT applications
	Water	71.4%	12.4%	In this experimental works, they study the use of forced water circulation through the spiral flow heat exchanger, to achieve thermal and electrical efficiencies.
3	PV/ water	55%	At Tα=15 ºC 12.8%	Tested the PVT models in outdoor at a steady state operation condition. For heat removing, in the first test, use water, in the second use the air. In both cases, water and air were controlled. Different cases by changing the PV-cell, and the cover.
	PV/ water + glazing	71%	-------	
	PV/ air	38%	At Tα=15 ºC 12.6%	
	PV/air + glazing	59%	-------	
4	PV/ water without reflector	46.76%	5.08%	In this paper, the experimentally work to compare between two set up, one with reflectors and other without. And give the efficiency calculation for the thermal and electricity for both sets up.
	PV/water + reflector	36.98%	3.69%	
17	water	33%	6.7%	For a combined PV-thermal collector, 4 numerical models have been built, to explain and compared the numerical results with the experimental results.

Chapter 3.

3. Design of PVT-Collector and built the system.

3.1. Introduction:

The main objective of this experimental study is to discuss the proposed practical design of PVT-collector and evaluate its thermal and electrical efficiency. A comparison of thermal and electrical efficiency is done between the study's proposed system (PVT-collector design) and the other two conventional systems (thermal collector, and PV panel). Also studying the using of paraffin wax as phase change material (PCM) in order to preserve the water temperature in the PVT-collector's pipes. The experimental set up consists of: a thermal collector with storage tank, separate PV-panel and PVT-collector with another storage tank. These systems were built and tested using the same tilt angle and at the same location.

This chapter describes the experimental setup, the design of PVT-collector, and testing and evaluation procedures.

3.2. Experimental setup:

In the first, the PVT collector is experimentally designed and is installed with the other thermal collector. The second is a conventional PV-panel in its own area, in order to quantify the thermal and electrical efficiency for these systems and compare between them. The experimental prototype was built on the top roof of building in coordinates (31°26 N, 35°05 E), Palestine, from February till May 2019. The climate of this area is moderate, an average annual temperature of 18 °C. The warmest month of the year is July, with average temperature 32°C.

The prototype as shown in figure (3.1) and (3.2), was constructed in which the separate solar thermal collector was connected to a storage tank. The experimental design of the PVT-collector was connected to another separate storage tank, in order to study each system separately. By using flexible plastic piping separated between the two systems, the cold water supplied from a source to the systems, and supply the hot water from the two systems to the consumer. The water circulated through two system by gravity. The separate PV-panel and the PV-panel which combined in PVT collectors are connected to voltmeter and ammeter and with a variable resistive load, to measure the volt and current to plot the I-V and P-V curves.

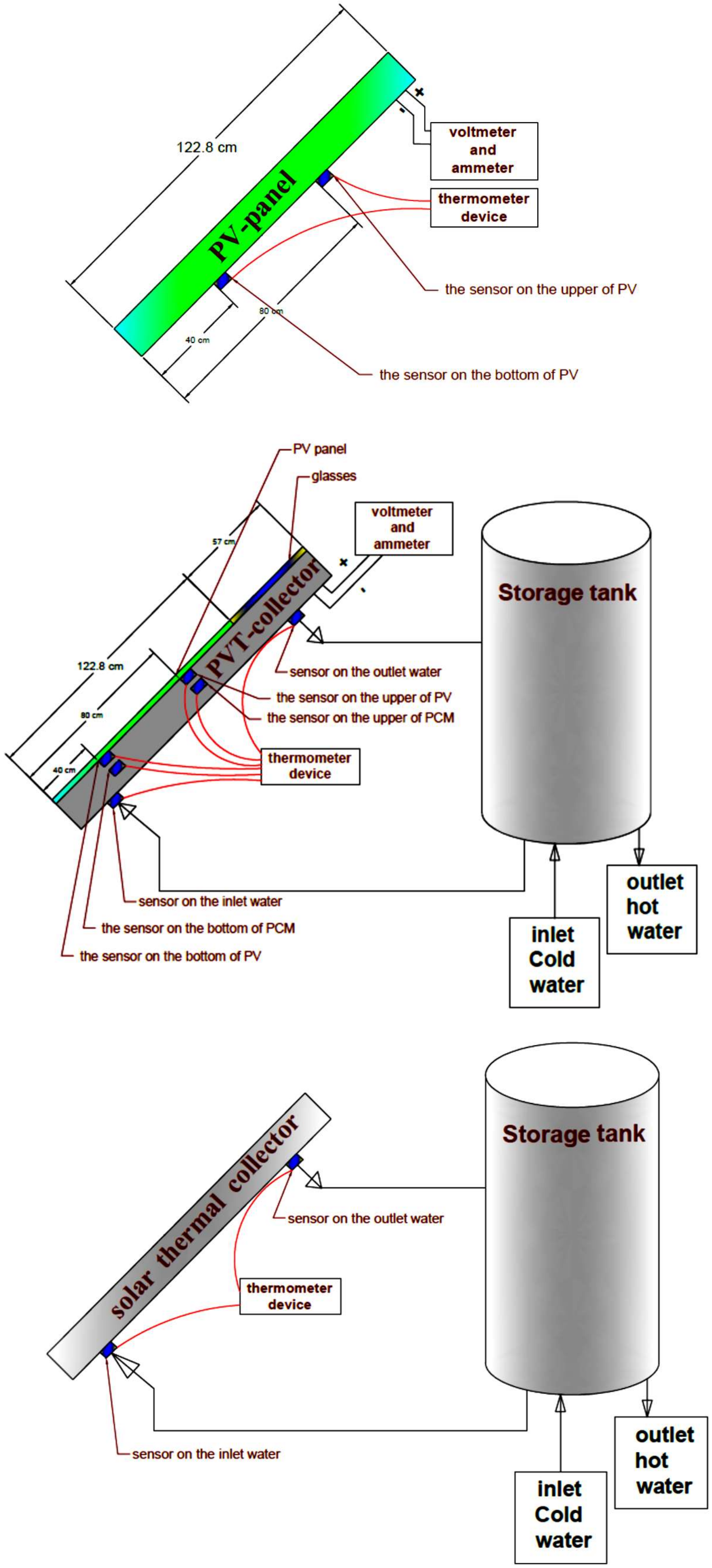

Figure 3. 1: Schematic experimental set-up

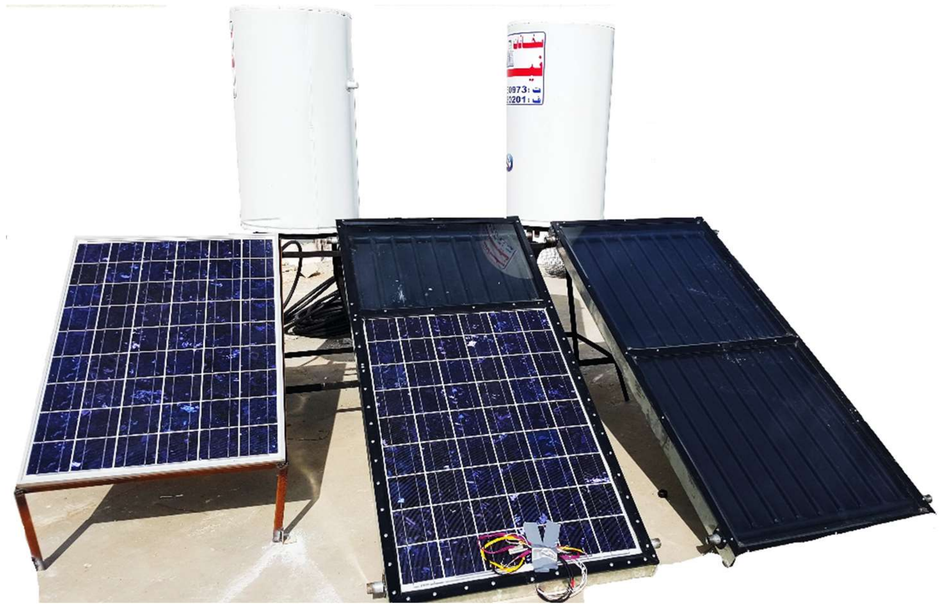

Figure 3. 2: Experimental prototype of all system: PVT-collector, thermal collector, PV panel

3.2.1. PV collector panel:

A photovoltaic panel type which was selected for the experiment is shown in Figure (3.3). It was manufactured by Photo watt Co. in France. Table (3.1) shows the specifications of this panel, which were taken under standard test conditions (STC) (*insolation 1000W\m^2, AM 1.5, cell temperature 25 ^{o}C*). The non-standard remark, is about the dimensions of this type, compared with the other types that was manufactured for Commercial purposes.

Figure 3. 3: PV-panel which was chosen to the experiment

Table 3. 1: Characteristic of the PV panel

Nominal voltage	18 V
Typical peak power (P_{max})	115 W
Voltage at peak power (V_{mp})	25.4 V
Current at peak power (I_{mp})	4.5 A
Short circuit Current (I_{SC})	4.7 A
Open circuit voltage (V_{OC})	31.9 V
Minimum power (P_{min})	109.3 W
Maximum system voltage	770V
Minimum bypass diode	6 A
Series fuse	8 A

A test of the PV panel was carried out by the solar panel examination unit at the Palestine Polytechnic University (PPU), as shown in figure (3.4). The results obtained were relatively identical to the data recorded on the PV panel according to the circumstances in which the test was performed.

Figure 3. 4: test the PV panel by solar panel examination

Table (3.2) shows the test characteristics of the first PV panel, and figure (3.5) shows the I-V and P-V curves

Table 3. 2: Characteristics of the first test PV panel

Model area(cm2):	**14256.00**
Sensor temp (??):	21.4
Irradiance(mW/cm2):	108.7
Isc(A):	5.0171
Voc(V):	31.9375
Pmp(W):	115.4462
Imp(A):	4.4589
Vmp(V):	25.8914
F.F.:	72.05
Module eff.(%):	7.45
Est. shunt resistance(ohm):	46.3837
Est. Series resistance(ohm):	0.5970

Figure 3. 5: PV-curve and I-V curve of first PV-panel test

Table (3. 3) show the test Characteristics of the second PV panel, and figure (3. 6) show the I-V and P-V curves.

Table 3. 3: Characteristics of the second test PV panel

Model area(cm2):	**14256.00**
Sensor temp (??):	22.3
Irradiance(mW/cm2):	108.9
Isc(A):	5.0411
Voc(V):	32.1534
Pmp(W):	116.0137
Imp(A):	4.5106
Vmp(V):	25.7204
F.F.:	71.57
Module eff.(%):	7.48
Est. shunt resistance(ohm):	48.4833
Est. Series resistance(ohm):	0.6517

Figure 3. 6: PV-curve and I-V curve of second PV-panel test

3.2.2. Flat plate collector panel:

In order to compare the performance of the thermal and photovoltaic panels, which were discussed in this thesis, two thermal solar panels have been provided. The first thermal panel will be integrated with the photovoltaic panel. The shape and design specifications adopted will be discussed later, while the second thermal panel, Figure (3.7), remains in its original state. Within the following specifications, Table (3.4):

Figure 3. 7: Thermal solar panels collector used

Table 3. 4: Specifications of thermal collector panel.

Outside Diameter of the main pipe (mm^2)	34	**Length of the main pipe (cm)**	98
Inside diameter of the main pipe from the (mm^2)	28	**Length of Sub-pipes (cm)**	171
Outside diameter of Sub-pipes (mm^2)	22	**Number of main pipe**	2
Inside diameter of Sub-pipes (mm^2)	18	**Number of Sub-pipes**	9
Dimensions of the metal box structure (cm)	182×87	**The distance between the sub-pipes (cm)**	9.5
Dimensions of the glass plate (cm)	91×82	**The type of insulation used below the pipe**	Politian
Thickness of glass (mm)	3	**Absorption thickness(mm)**	0.4

3.2.3. Storage tank:

Two storage tanks used in the experiment are shown in figure (3.8). Both are manufactured by Nairoukh Factory for a domestic use with (42 L) capacity. One is connected with thermal collector, whereas the other is connected with the experimental PVT collector. Table (3.5) show the specifications of the Tank.

Figure 3. 8: The storage tanks used

Table 3. 5: The specifications of the storage tank

Outer diameter tank (cm)	38	**Thickness of insulation material (cm)**	4
Inner diameter tank (cm)	30	**Volume of the tank in liters**	42
Outer tank thickness (mm)	0.4	**Inner tank thickness**	3
Diameter pipes in the tank (mm^2)	27		

3.2.4. A phase change material (Paraffin Wax 58/60):

For the experimental design of the PVT-collector, rely on the use of the Paraffin Wax with melting temperature (58/60) as in, Figure (3.9), where it’s a saturated hydrocarbons material called alkanes, like a phase change material (PCM).

Paraffin Wax is good thermal insulation material, and it can be used to store heat when it converted from solid to liquid, and then this stored heat can be used later in a system [33].

Figure 3. 9: Paraffin Wax (58/60)

3.2.5. Auxiliary devices and Accessories:

There are several auxiliary devices and Accessories used to complete the construction of the study model including as shown in, Figure (3.10):

- 25mm^2 plastic pipes.
- Holder for 2 collection tanks.
- Copper connections for connecting plastic pipes and panels on one side, and between panels and tanks on the other hand.
- Sensors and thermometer device.
- Voltmeter and ammeter to measure the voltage and current of the PV panels.
- Variable resistance connected with PV panels to draw I-V curve.
- IR for hotspot detection on PV panels.
- The values of solar radiation have been based on the daily readings carried out by the system at the Palestine Polytechnic University, which is supervised by the Department of Integration with Industry.

Figure 3. 10: Auxiliary devices and Accessories used in this experiment

3.3. Measurements:

3.3.1. Current and voltage measurement:

The current and voltage produced by the two separate PV panels are measured using two voltmeters and two ammeters, at different times and with different sun radiation values. Measurement of current and voltage is obtained when connected variable resistive load, to plot I-V and P-V curve for every PV panel.

3.3.2. Temperature measurement:

There are many temperatures that were measured, using a thermocouple sensor connected to the thermometer device. They are temperature of inlet and outlet water for the thermal collector and the PVT collector, the temperature of Paraffin wax inside the PVT collector in two position, the temperature of the PV panel that is combined with PVT collector in two position, and the temperature of the separate PV panel in two positions as will as the ambient temperature.

3.4. Experimental procedure:

A series of steps and preparations were made to make comparisons between the three types of solar panels which are: an independent solar thermal panel, and a photovoltaic-thermal panel, and the independent photovoltaic panel. They are illustrated in the following sub-section:

3.4.1. Design and Fabrication of PVT-collector:

The design and construction of a thermal photoelectric panel, through which the production of electricity on one hand and the heating of the water flowing in the pipes inside it in the other hand using the following order of steps:

1- The metal body with Dimensions of (182 cm ×87cm) and thickness of (0.4mm), contains carton insulation with thickness 1 cm under the pipe structure as shown in Figure (3.11).

Figure 3. 11: Metal body with carton insulation and pipe structure

2- Installing a black metal absorber over the pipe in the top of collector, Figure (3.12).

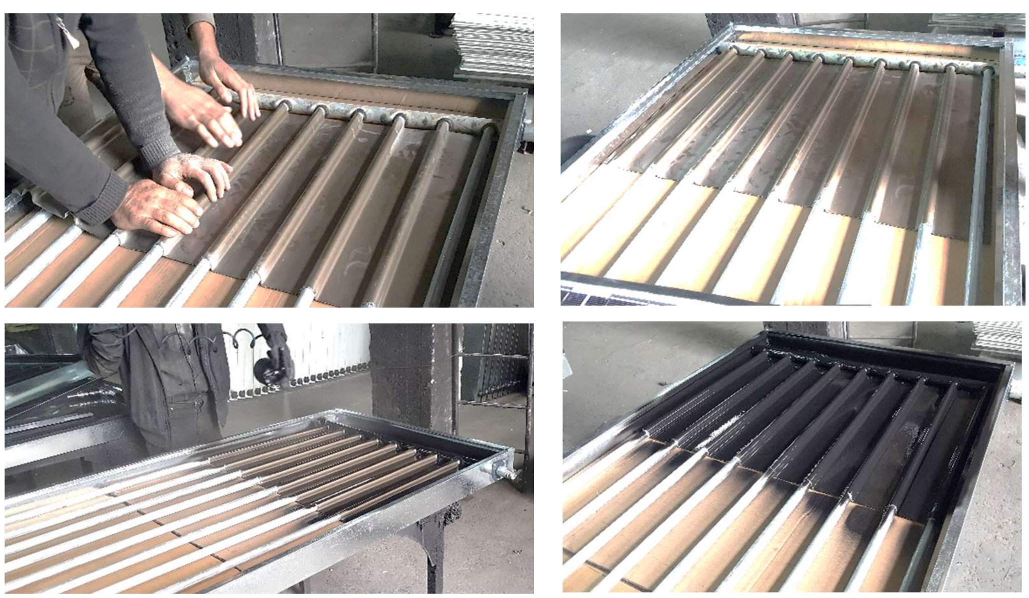

Figure 3. 12: Install a black metal absorber over the pipe

3- Close all openings in the metal body, such as the outlet of the pipes and the corners of the metal body, using transparent liquid silicone and plastic sheeting, Figure (3.13).

Figure 3. 13: Close all openings in the metal body

4- A separation between the upper and lower sections of the panel, in which the photovoltaic panel will be installed after pouring the paraffin wax material, Figure (3.14).

Figure 3. 14: A separation between the upper and lower sections of the panel.

5- Installing the internal heat sensors, which will be used to measure the temperature of the paraffin wax material, and closure of the side edges of the metal sheet with foam material to prevent the leakage of liquid paraffin wax material when poured into the board to surround the tubes, Figure (3.15).

Figure 3. 15: Installing the internal heat sensors and closure of the side edges of the metal sheet with foam material.

6- Dissolving the paraffin wax material, and then pour it into the panel to submerge the pipe and surround it from all sides, Figure (3.16).

Figure 3. 16: Dissolving the paraffin wax material and then pour it into the panel.

7- Install the heat sensors under the photoelectric panel, which will be integrated with thermal collector, to measure the temperature of the photoelectric panel, Figure (3.17).

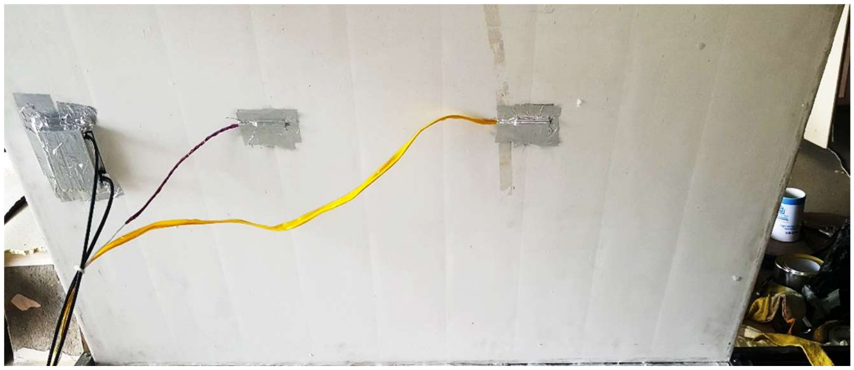

Figure 3. 17: Install the heat sensors under the photoelectric panel.

8- Install the photoelectric panel in the custom location which is above paraffin wax, Figure (3.18).

Figure 3. 18: Install the photoelectric panel in the PVT-collector.

3.4.2. Installation and assembly the system:

For the required study, the system was installed in the same place and with the same tilt angle as follows:

- Installation of a separate photovoltaic panel on holder structure.
- Installation of the solar thermal collector and connected it with a storage tank.
- Installation of the PVT collector and connected it with another storage tank.
- Connecting the thermocouple temperature sensors with thermometer device, to measure the temperature of, Figure (3.19):
  - Water in the inlet and outlet of the thermal collector.
  - Water in the inlet and outlet of the PVT- collector.
  - The photovoltaic panel from the back, which was installed on PVT-collector.
  - The photovoltaic panel from the back, which was installed alone.
  - The Paraffin wax material which was used in PVT- collector.
  - The ambient.

Figure 3. 19: Installing the thermocouple sensors.

❖ Connecting the PV-panel terminals to the measuring device, figure (3.20):

Figure 3. 20: Connecting the PV-panel terminals to the measuring devices.

Chapter 4.

4. Experimental study of the PVT-collector design.

4.1. Introduction:

To examine the performance of the designed PVT collector, the proposed system is evaluated and tested between Februarys and May 2019 under different weather condition. Some of these days was clear and others were cloudy. This helps to analyze the difference between the results obtained and determine the effect of weather on the performance. The results of the experiment include the power generated from the conventional PV panels and the PV combined in PVT collector, the inlet and outlet water temperature in the thermal collector and PVT collector, the temperature of the Paraffin wax inside the PVT collector, are presented and analyzed in this section.

The performance of a PVT collector and thermal collector be described by the efficiency. In the thermal collector it is just thermal efficiency. But in PVT collector the efficiency is a combination of thermal efficiency (η_{th}) and electrical efficiency (η_{el}), equation (1):

$$\eta_{C,PVT} = \eta_{th} + \eta_{el} \qquad (1)$$

As mentioned before, the final aim of this thesis is to compare the experimental PVT design, with a traditional types of thermal collector and PV panels. The obtained results are analyzed for the thermal efficiency, which calculated by equation (2), and electrical efficiency, which calculated by equation (3).

$$\eta_C = \eta_o - a_1 \frac{(T_i - T_a)}{G} - a_2 \frac{(T_i - T_a)^2}{G} \qquad (2)$$

η_c : Collector efficiency.

η_o : Maximum efficiency if there is no heat losses (optical efficiency) (0.78).

a_1 : First order heat losses coefficient (3.2 W/k.m^2).

a_2 : Second order heat losses coefficient (0.015 W/k^2.m^2).

T_i : Inlet fluid temperature of the collector (ºC).

T_a : Ambient temperature (ºC).

G : Total solar radiation on the collector surface.

$$\eta_{el} = \frac{V_m I_m}{G A_c} \qquad (3)$$

Where:

- η_{el} : The electrical efficiency.
- V_m and I_m are the value of voltage and current respectively that give maximum power production.
- A_c : Collector area.

The following sections report the results of the experimental test of these system.

4.2. Electrical characteristic:

For the investigated system, Figure (4.1) and (4.2) show, for a non-net day (20 Feb., 13:43 PM), the I-V and P-V curve for the conventional PV panels (PV_{CO}) and the PV combined in PVT collector (PV_{PVT}), respectively. These figures show the distortion in the I-V curve for both PV panels, and that is because no consistency in solar radiation in that day. The power values for PV panel (PPV) reached a maximum of (35.7 W), and the value for PVT collector (PPVT) was (35.21 w). This result depends on the value of solar radiation at that time -which did not exceed (415 W/m^2)- . By using equation (4) to calculate the fill factor (FF). FF for PV-panel is (0.46) and for PVT is (0.41). Using equation (3), the electric efficiency for the (PV_{CO}) and (PV_{PVT}) was the same (6%).

$$Fill\ Factor\ (FF) = \frac{Power\ at\ the\ maximum\ power\ point}{V_{OC} I_{SC}} = \frac{V_m I_m}{V_{OC} I_{SC}} \qquad (4)$$

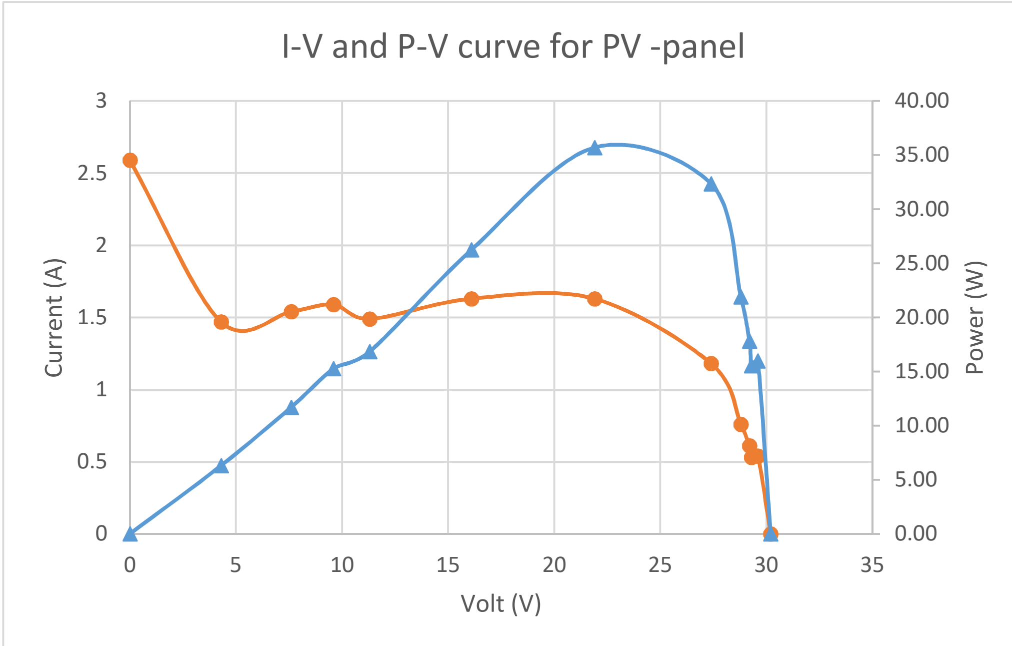

Figure 4. 1: I-V and P-V curve of the conventional PV-panel, in (20 Feb.), 13:45 PM.

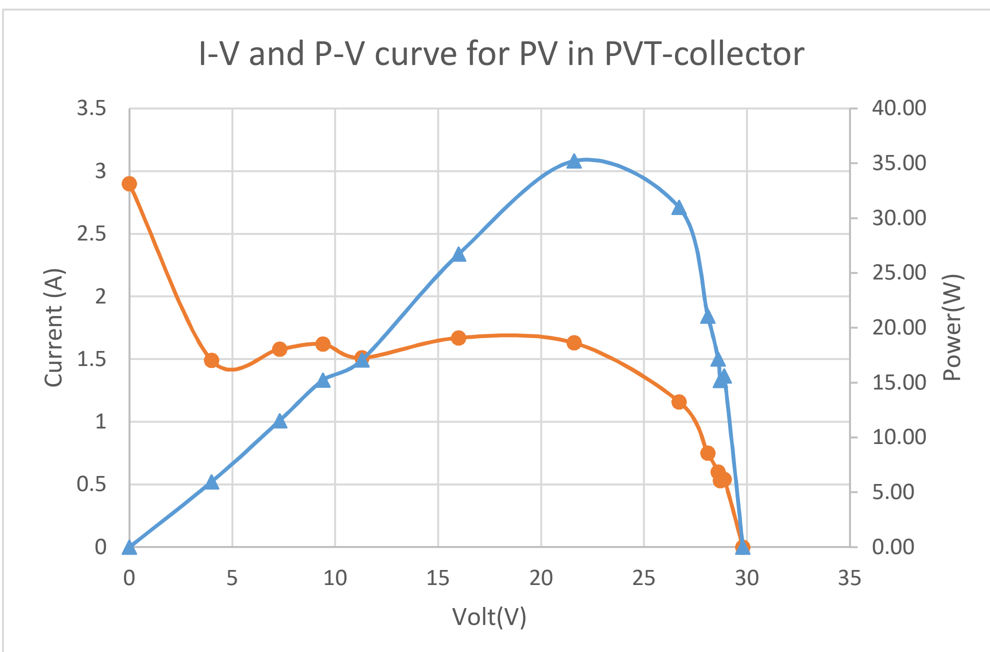

Figure 4. 2: I-V and P-V curve of the PV-panel combined in PVT collector, in (20 Feb.), 13:45 PM.

Figures (4.3), (4.4), (4.5), shows the comparison in PV-curve, between the (PV_{CO}) and (PV_{PVT}) in different sunny days. In (23 Feb.), maximum power point (MPP) produced by (PV_{CO}) was (21.7 w) and (PV_{PVT}) was (19.66 W). FF of (PV_{CO}) and (PV_{PVT}), (0.66) and (0.64), respectively. The electric efficiency was (8%) for (PV_{CO}) and (PV_{PVT}).

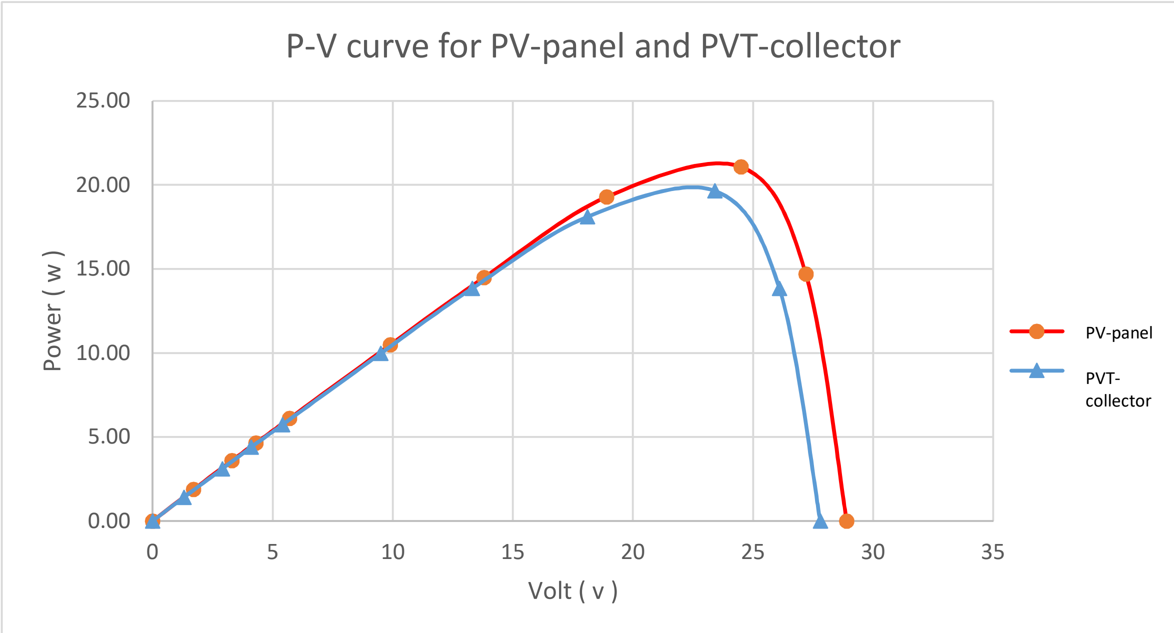

Figure 4. 3: P-V curve of the conventional PV-panel, and PV in PVT collector. In (23 Feb.), 14:00 PM.

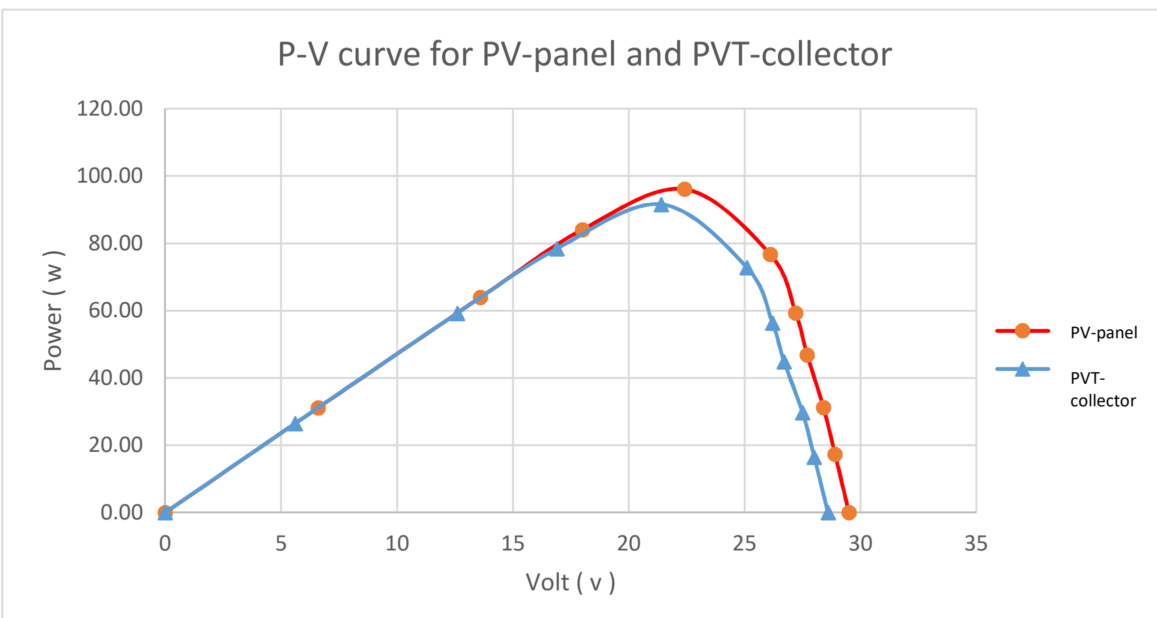

Figure 4. 4: P-V curve of the conventional PV-panel, and PV in PVT collector. In (13 Mar.), 13:10 PM.

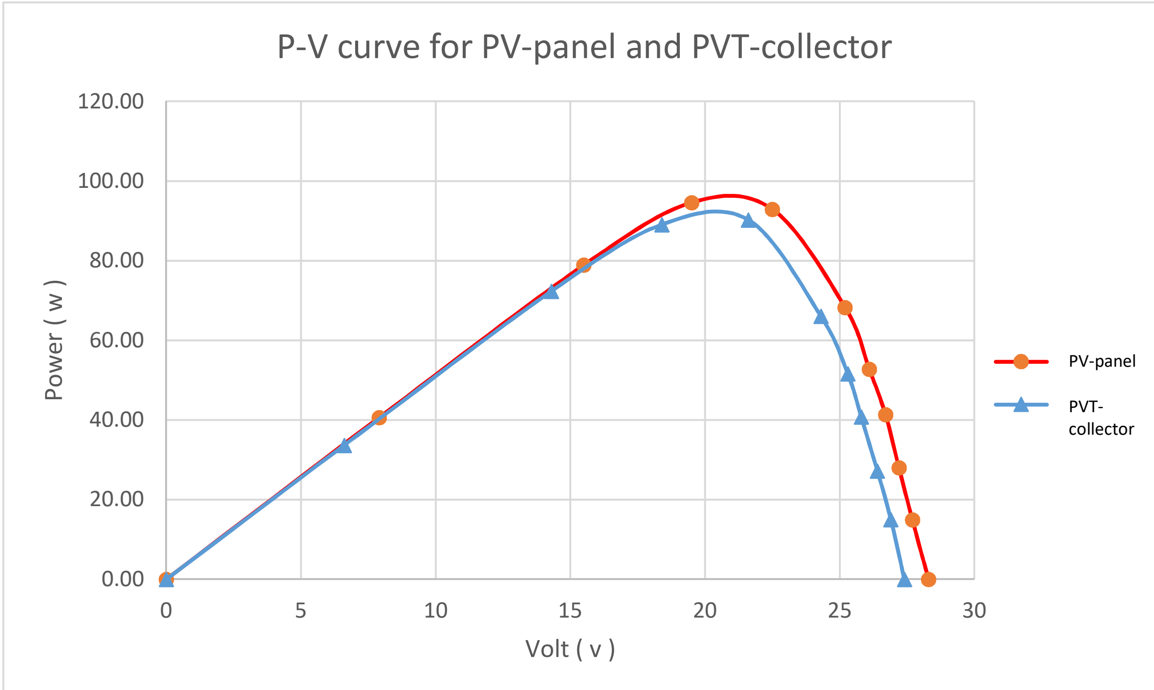

Figure 4. 5: P-V curve of the conventional PV-panel, and PV in PVT collector. In (11 Apr.), 14:00 PM.

In (13 Mar. /13:10 PM), with solar radiation (G) = (890 W/m^2), the maximum power point (MPP) for (PV_{CO}) reached (96.1 W) at voltage (V_m) = (22.4 V), and current (I_m) = (4.29 A). The FF = (0.68), and with electric efficiency (η_{el}) = (8%). For (PV_{PVT}), MPP= (91.59 W) at V_m= (21.4 V) and I_m= (4.24 A). The FF = (0.67), and η_{el} =7%. The sun radiation in (11 Apr. /14:00 PM) is (883 W\m^2), the MPP for PV = (94.58 W), V_m = (19.5 V), I_m = (4.85 A). The FF = (0.65), η_{el} = (8%). For PVT, MPP = (90.29 W), V_m = (21.6 V), I_m = (4.18 A). The FF = (0.64), η_{el} = (7%). It can be observed from this data, that at a high solar radiation values the electricity production are high. On the other hand, if the values of solar radiation are close at different days of collecting data, the resulting energy is also close.

Table (4.1) shows data collected at different dates and times for voltage, current and radiation, which was used to calculate the maximum power, fill factor and electrical efficiency. Difference in maximum power produced depend on several factors. One of these factors is the solar radiation. One can see in (4 Mar. at 13:19) the maximum power is (24.96 W, 24.93 W) for (PV_{CO}) and (PV_{PVT}) respectively at (193 W/m^2). Comparing with (11 Mar. at 13:30) the maximum power is (95.42 W) for (PV_{CO}) and (90.31 W) for (PV_{PVT}), at (867 W/m^2) solar radiation. On other hand, the increase of radiation may affect the electrical efficiency, that's because they increase the cells temperature in the PV panel. In (21 Feb.), the electrical efficiency and fill factor of (PV_{CO}) and (PV_{PVT}) is (13%) and (0.7), respectively. compare with (11 Apr), the electrical efficiency of (PV_{CO}) is (8%) and fill factor (0.65), and for (PV_{PVT}) is (7%), and F.F (0.64), at solar radiation (883 W/m2).

Table 4. 1: Data collected at different dates and times, to calculate MPP, F.F and η_{el}

Data/ time	**Type**	**V_m (V)**	**I_m (A)**	**MPP (W)**	**Radiation (W/m^2)**	**Ambient (^OC)**	**F.F**	**η_{el} (%)**
25 Feb. at 13:45 PM	PV	21.5	4.14	89.01	756	25	0.68	8
	PVT	20.2	4.06	82.01			0.66	8
4 Mar. at 13:19 PM	PV	20.8	1.2	24.96	193	15	0.63	9
	PVT	20.6	1.21	24.93			0.66	9
11 Mar. at 13:30 PM	PV	22.4	4.26	95.42	867	20	0.69	8
	PVT	21.3	4.24	90.31			0.68	7
4 Apr. at 10:00 AM	PV	25.8	2.78	71.72	546	20	0.64	9
	PVT	25.5	2.81	71.66			0.63	9
4 Apr. at 12:35 PM	PV	22.6	4.19	94.69	771	25	0.64	9
	PVT	21.5	4.19	90.09			0.58	8
11 Apr. at 14:00 PM	PV	19.5	4.85	94.58	883	24	0.65	8
	PVT	21.6	4.18	89.06			0.64	7

Summary:

The power produced by the (PV_{CO}) and (PV_{PVT}), affected by solar radiation from sunrise to sunset. Where it increases from sunrise to noon, then it decreases from noon to sunset. The electrical efficiencies of PV and PVT are very close to each other, but the PVT give more product than the PV, it give a thermal product. The electrical efficiency of PV is negatively affected when the temperature of the cells increases more.

4.3. Thermal characteristic:

PV panel has two important parameters, short circuit current (I_{sc}) and open circuit voltage (V_{oc}). These parameters are affected by incident solar radiation (G) and the ambient air temperature (T_a). At high radiation the temperature of the PV panel increases and its efficiency will decrease. Figure (4.6) shows the effect on I-V curve and P-V curve at different temperature. Equation (5), is used to calculate the PV panel temperature (T_C), where NOCT is the normal operating cell temperature.

$$T_C = T_a + \frac{NOCT - 20}{0.8} G \quad (5)$$

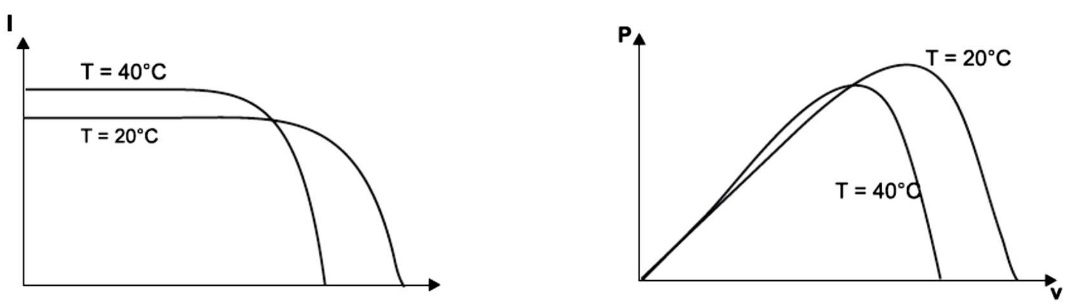

Figure 4. 6: I-V and P-V curve characteristics of a PV cell at different temperature [10].

As in figure (4.7), Matching in I-V curves for PV_{CO} and PV_{PVT} is very clear. This data collected in (21 Feb.) at 9:00 AM. The temperature in back of conventional PV and PV in PVT is shown in table (4.2). T_{up}, T_{do} is the temperature up side and down side respectively, of the conventional PV panel (PV_{co}) and the PV panel in PVT collector (PV_{PVT}). The temperature of PV_{CO} and PV_{PVT} is closed together, where the solar radiation is not very high to increase the PV cells temperature.

Table 4. 2: Temperature upside and down side, for PV and PV in PVT

Type	T_{up} (ºC)	T_{do} (ºC)	Diff (ºC)
PV-panel	26	25	1
PV in PVT	25	25	0

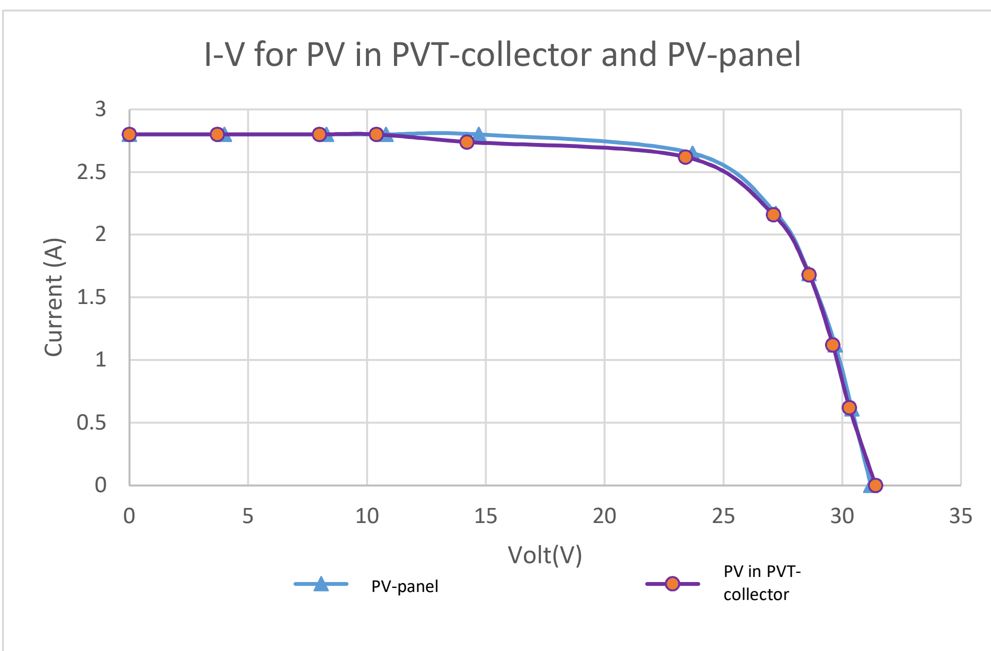

Figure 4. 7: I-V curve for conventional PV-panel and PV in PVT-collector. (21 Feb. at 9:00 AM)

The effect of increase temperature on I-V curve is shown in figure (4.8). This data in (19 Mar.) at 12:55 PM, and with sun radiation (924 W/m2). For PV_{co}, T_{up} is (55 ºC) and T_{do} (54 ºC). And for PV_{PVT}, T_{up} is (69 ºC) and T_{do} (68 ºC). One of the main reasons for the different between the temperature of the PV_{co} and PV_{PVT} is, the cooling system. The air moving behind the PV_{co} and its work as a cooler. In PV_{PVT} there is a thermal insulator which is Paraffin wax behind the panel. Direct effect appears on open circuit voltage, where when the PV cell temperature increase more, the open circuit voltage (V_{OC}) be pulls on the curve to left, as shown in PV_{PVT} curve. The open circuit voltage (V_{OC}) for PV_{CO} is (28.5 V) and short circuit current (I_{SC}) is (5.1 A), and for PV_{PVT} the (V_{OC}) is (27.3 V) and (I_{SC}) is (5.1 A).

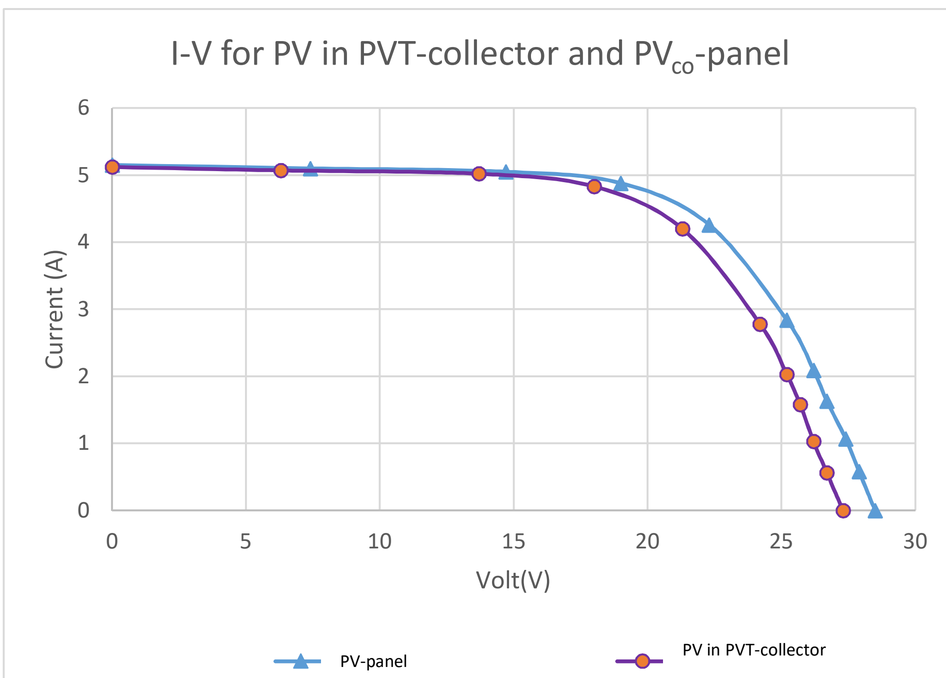

Figure 4. 8: I-V curve for conventional PV-panel and PV in PVT-collector. (19 Mar.). At 12:55 PM

Figure (4.9), shows the difference between the temperature of PV_{PVT} and PV_{CO} in (8 Apr.) from (7:45 Am) to (13:45 PM). In PV_{PVT} the temperature raise to (64 ºC) higher than PV_{CO} where it is (51 ºC). Which is the same like in figure (4.10), which turns out the T_{do} for both. The oscillation on the temperature curve, is because the oscillation in solar radiation, which it high at high solar radiation, and become low at low solar radiation. Table (4.3) show which collected in (8 Apr) from (7:45 AM) to (13:45 PM), the relation between solar radiation and the temperature of the PV_{CO} and PV_{PVT} from back upside and down side. At the beginning the temperature of PV_{CO} it was higher than PV_{PVT} in back upside and downside, but when the solar radiation increased more than (644 W/m^2) the temperature of PV_{PVT} began to increase more than PV_{CO}. The difference became larger, when the solar radiation became greater than (770 W/m2), where the difference between them more than (8 degrees). Another reason that affected this result is the wind, which is works as a coolant for the PV_{CO}. The temperature of PV_{CO} and PV_{PVT} start to be decrease with decreasing the solar radiation.

Table 4. 3: Relation between the solar radiation and temperature of PV_{CO} and PV_{PVT} in (8 Apr.).

Time	**Radiation (W/m2)**	**Wind (Km/h)**	**T_{up} (PV_{CO})(^{O}C)**	**T_{do}(PV_{CO})(^{O}C)**	**T_{up}(PV_{PVT}) (^{O}C)**	**T_{do}(PV_{PVT}) (^{O}C)**
7:45	388	1.8	18	18	16	16
8:20	557	1.8	21	20	18	18
8:50	644	4.3	30	30	32	31
9:20	710	0	33	34	38	37
9:50	791	3.2	40	40	45	44
10:20	770	10.1	45	44	53	50
10:50	955	8.3	49	48	58	55
11:20	990	0	46	45	57	55
11:50	1000	2.2	51	51	63	61
12:20	892	6.1	51	51	64	63
13:20	886	2.9	49	48	64	63
13:45	853	4.3	46	45	61	61

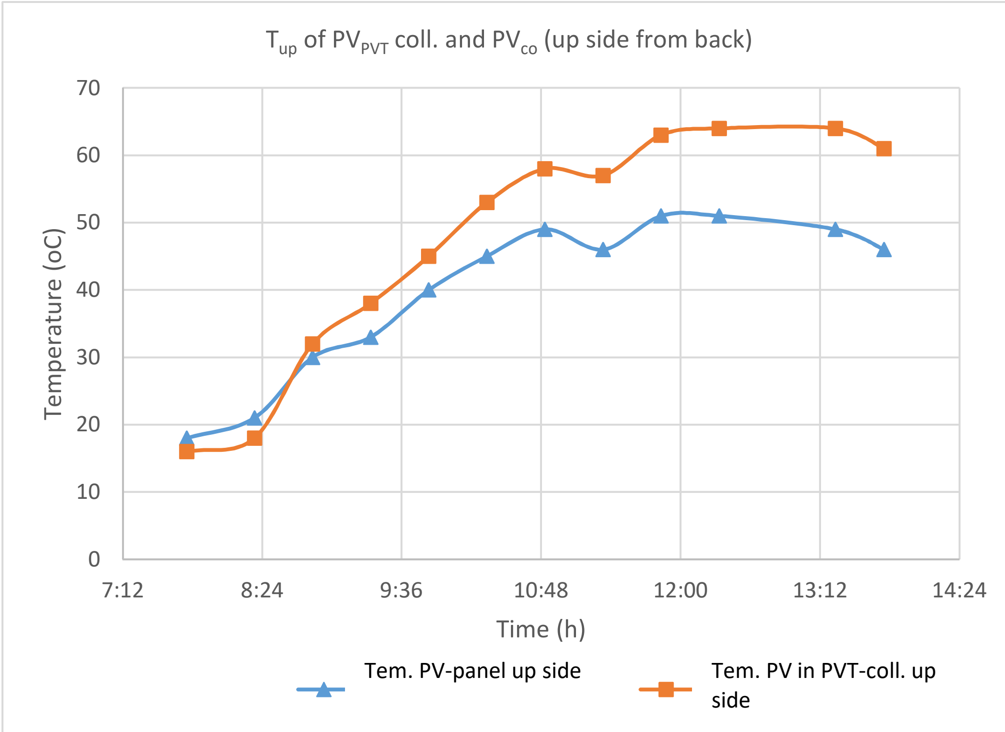

Figure 4. 9: Temperature of PV-panel in PVT collector and PV-panel (in back from upside). (8 Apr.)

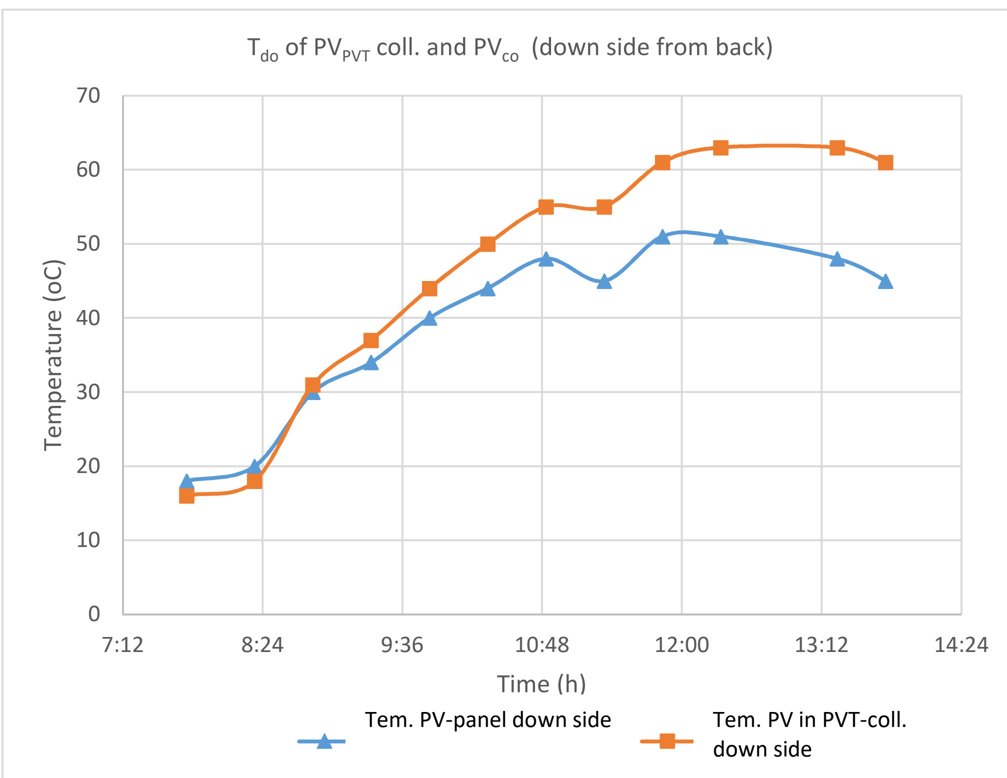

Figure 4. 10: Temperature of PV-panel in PVT collector and PV-panel (in back from down side). (8 Apr.)

The relation between T_{up} of PV_{CO} and PV_{PVT} with radiation appears in figure (4.11). The temperature of PV in PV_{PVT} and PV_{CO} steadily increases with increase in solar radiation, but in PV_{PVT} is more than in PV_{CO}. The temperature in back form upside of PV_{PVT} raised to (64 ^{O}C), higher than the temperature in PV_{CO} which is (51 ^{O}C). One of the main reasons is of this is the cooling process, which that occurs for the PV_{CO} from the movement of air behind the panel. The same applies to the figure (4.12), which describes the relation between T_{do} of PV_{CO} and PV_{PVT} with solar radiation. The temperature in back form down side of PV_{PVT} raised to (63 ^{O}C), higher than the temperature in PV_{CO} which is (51 ^{O}C). Table (4.4) shows the electrical efficiency, the average temperature, for the PV_{CO} and PV_{PVT}, in (10 Apr.) at 14:00 PM. In spite the average temperature for PV_{PVT} is higher than PV_{CO} at the same ambient temperature and solar radiation, the electrical efficiency is the same.

Table 4. 4: Electrical efficiency of PV_{CO} and PV_{PVT} in (10 Apr.) at 14:00 PM

Type	T_{up} (^{O}C)	T_{do} (^{O}C)	Average. (^{O}C)	Ta (^{O}C)	Radiation (W/m2)	η_{el} (%)
PV_{CO}	51	50	50.5	24	884	8
PV_{PVT}	65	64	64.5			8

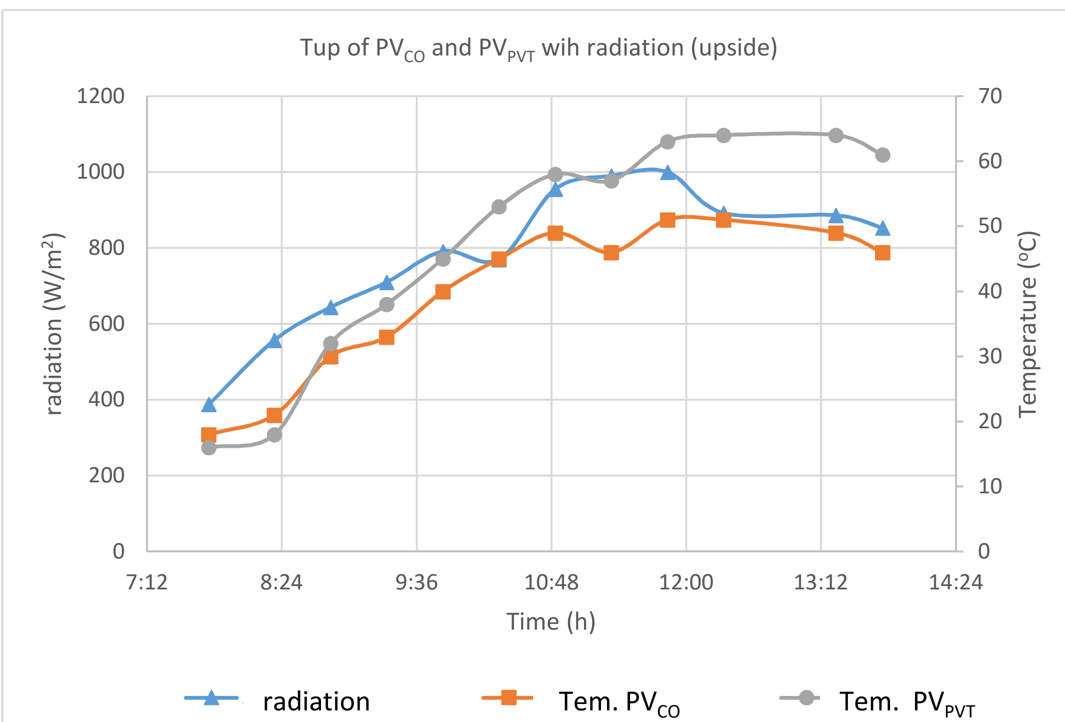

Figure 4. 11: Relation between PV temperature on PV_{CO} and PV_{PVT} and the solar radiation (in back from upside). (8 Apr.)

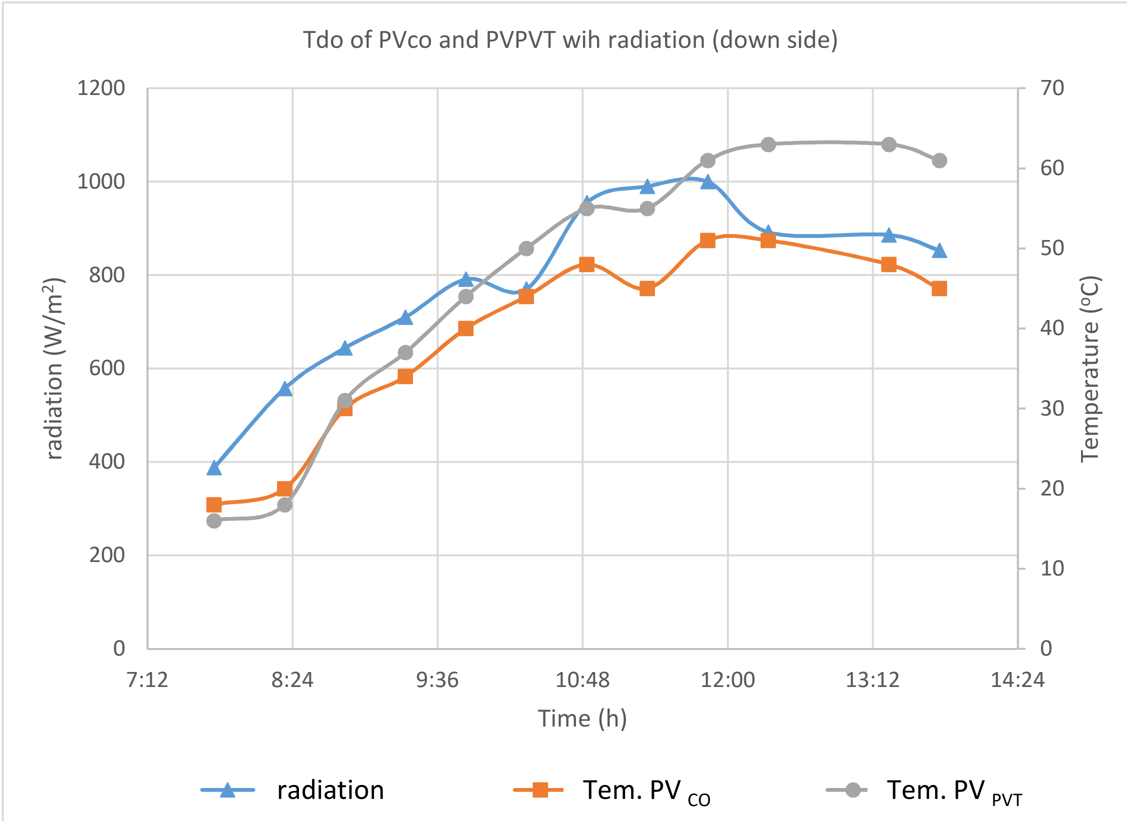

Figure 4. 12: Relation between PV temperature on PV_{CO} and PV_{PVT} and the solar radiation (in back from down side). (8Apr.)

Paraffin wax was used as phase change material in the PVT collector to work as an insulator, and to keep the temperature of water inside the PVT collector. The relation between PCM and solar radiation is shown in figure (4.13) and figure (4.14) which was collected in (9 Apr.) from (7:42 AM) to (15:10 PM). The increase of PCM temperature is related to increase in solar radiation. The maximum temperature of PCM upside was (30 ^{O}C), and in down side (34 ^{O}C). Figure (4.15) and figure (4.16), shows the relation between the solar radiation and the temperature of PV and PCM in PVT collector. It show the steady increase in the PV and PCM with increase in solar radiation to (972 W/m2), but when the solar radiation start to decrease, the temperature of PV and PCM still increase. That's because, in one hand, the PCM does not lose heat quickly but works to store it for long periods, in other hand, the temperature of water inside the PVT collector still hot, where it exchanges heat with the PCM.

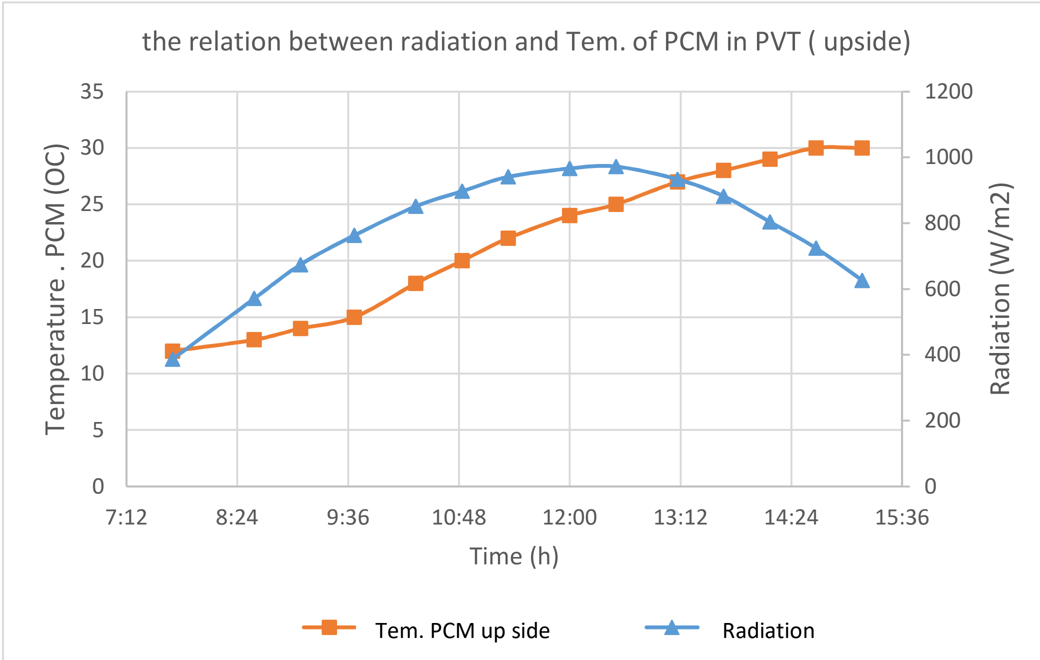

Figure 4. 13: Relation between radiation and temperature of PCM in PVT (upside). (9 Apr.)

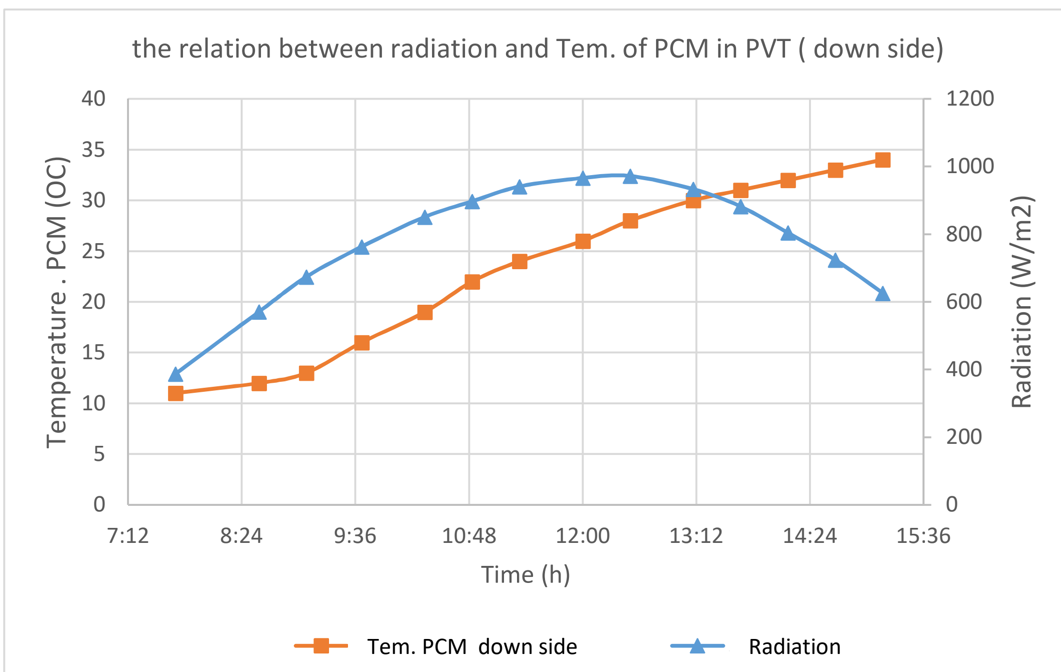

Figure 4. 14: Relation between radiation and temperature of PCM in PVT (down side). (9 Apr.)

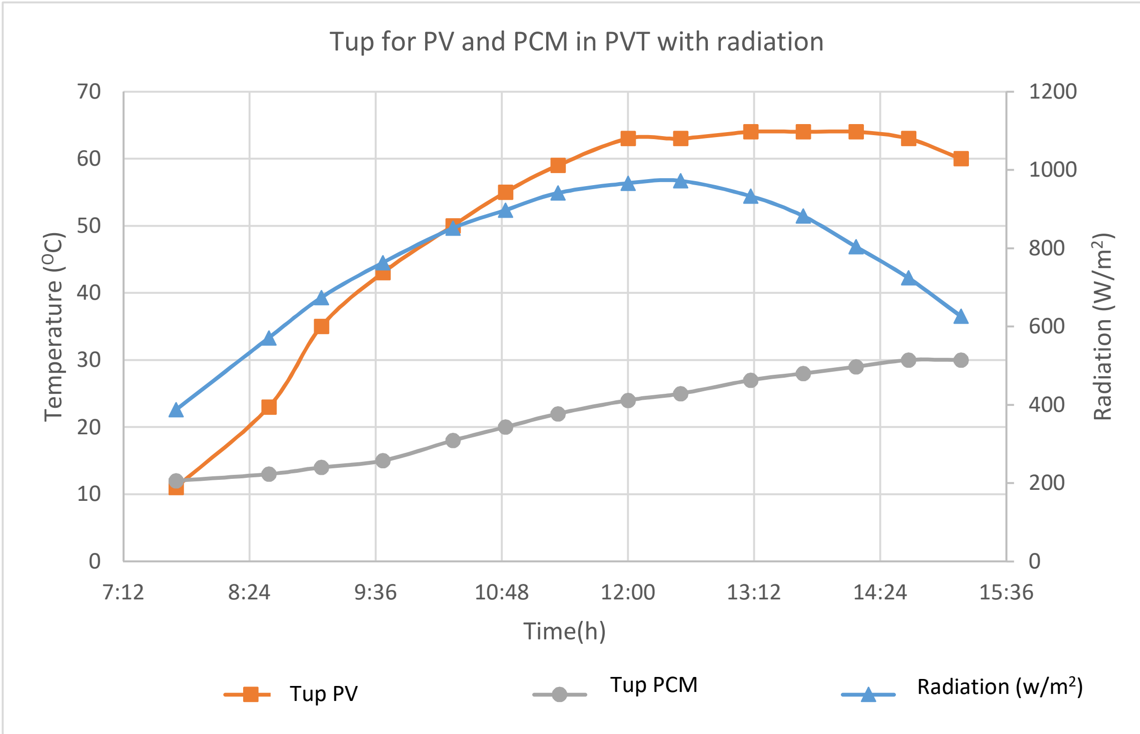

Figure 4. 15: Relation between radiation and the temperature of PCM and PV in PVT collector, (upside) in (9 Apr)

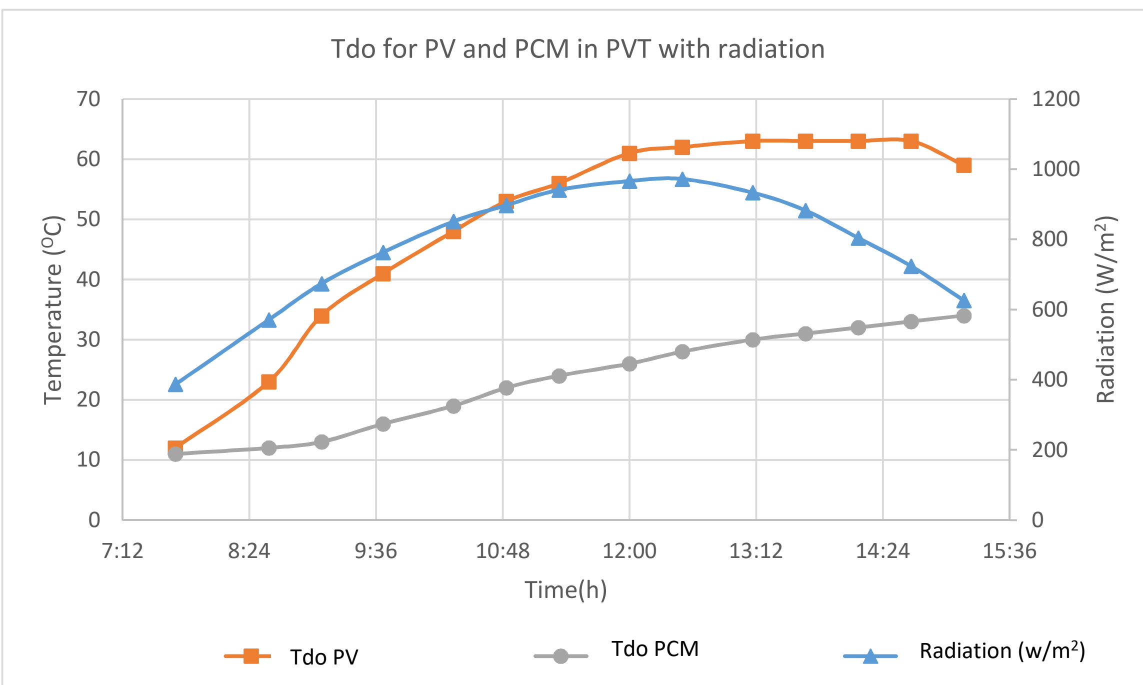

Figure 4. 96 : Relation between radiation and the temperature of PCM and PV in PVT collector, (downside) in (9 Apr)

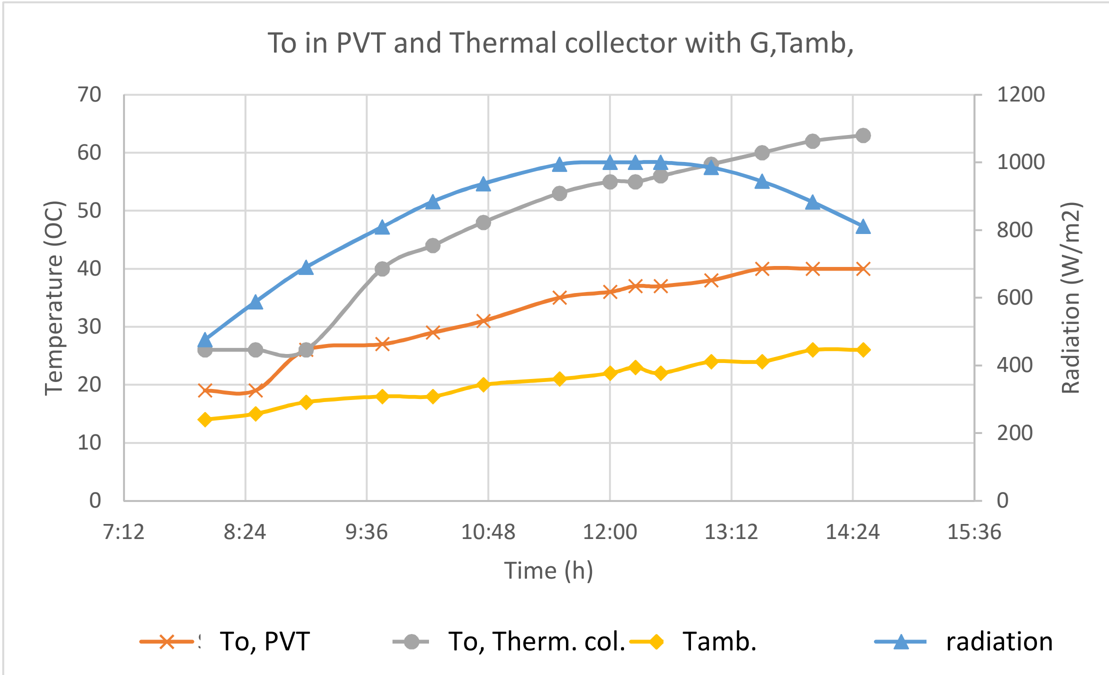

Figure 4. 107: Temperature of outlet water in PVT and thermal collector. (11 Apr.)

Figure (4. 17), shows the difference of increase temperature in outlet water in PVT and thermal collector when the solar radiation increases in (11 Apr.). The main reason of this difference is, in the thermal collector the incident solar radiation is reaches directly to the absorber which conduct the heat to water. But in the PVT collector the heat which is reaches to water comes from the back of PV panel through the convection by the Paraffin wax. The maximum outlet water temperature of PVT collector it was (40 ^{O}C), and for thermal collector is (63 ^{O}C), at solar radiation (883 W/m2) and with (26 ^{O}C) ambient temperature.

The same figure shows the relation between the solar radiation and the outlet water temperature for PVT and thermal collector. With increase solar radiation, the outlet water temperature (To) in both collector was increased. With increasing ambient temperature we observe a steady increase in outlet water temperature of collectors.

The PV_{CO} and PV_{PVT} temperature were measured by means of the infrared camera in (19 Mar.) as shown in figure (4.18) and (4.19). The red color describes the maximum temperature that was measured in the panel surfaces which is up to (71.6 ^{O}C) in PV_{PVT} and (68.2 ^{O}C) in PV_{CO}. The green color describes the medium temperature that was measured in the panel surfaces. This image was captured at (12:55 PM) with (924 W/m^2) solar radiation and ambient temperature (27 ^{O}C). It shows how much PV_{CO} and PV_{PVT} was affected by the solar radiation and the wind speed, in one hand the solar radiation increases the temperature of PV panel in both, but in PV_{CO} the wind cools the panel and makes temperature less than in PV_{PVT}. Figure (4.20) and (4.21), show the temperature images in (17 Feb.) at (12:55 PM) with solar radiation (296 W/m2) for PV_{PVT} and PV_{CO}, respectively. In these images the maximum temperature in PV_{PVT} surface is around (20 ^{O}C), and in PV_{CO} around (17 ^{O}C). Comparing these results with the mentioned results in (19 Mar.); the reason behind the different values is related to the higher value of solar radiation in (19 Mar.) than the value in (17 Feb.).

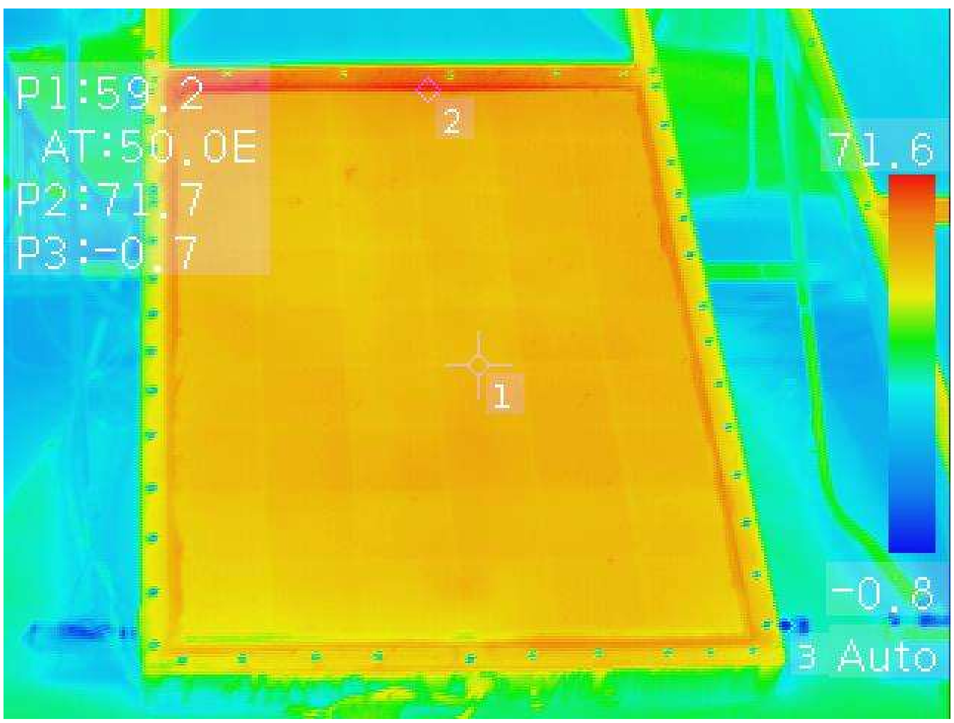

Figure 4. 18: PVT collector temperature by thermal imaging camera.
(19 Mar)

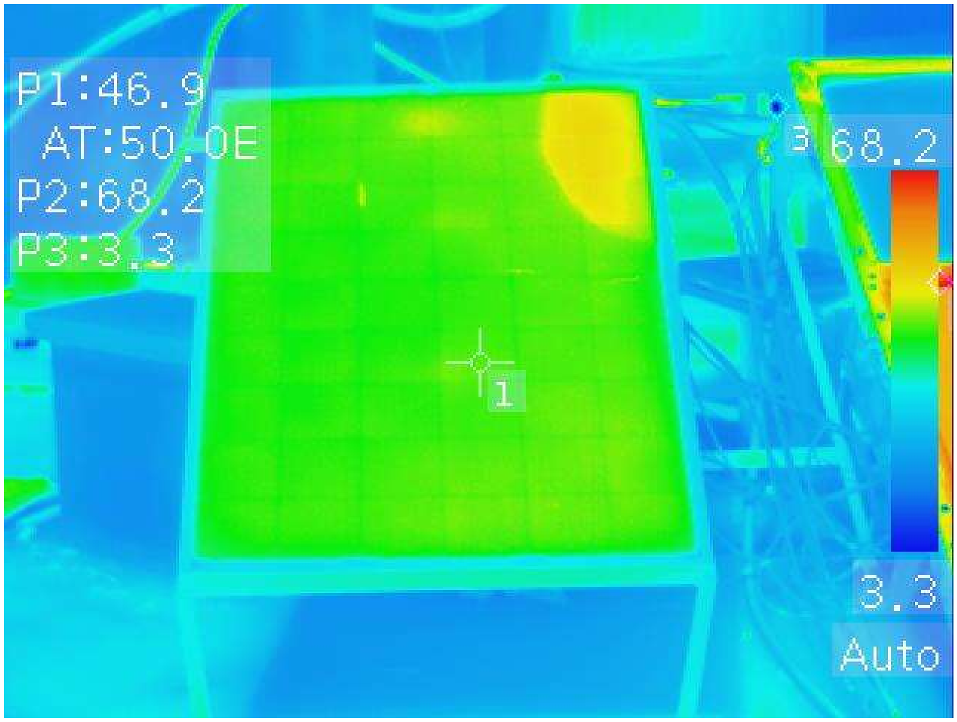

Figure 4. 19: PV panel temperature by thermal imaging camera. (19 Mar)

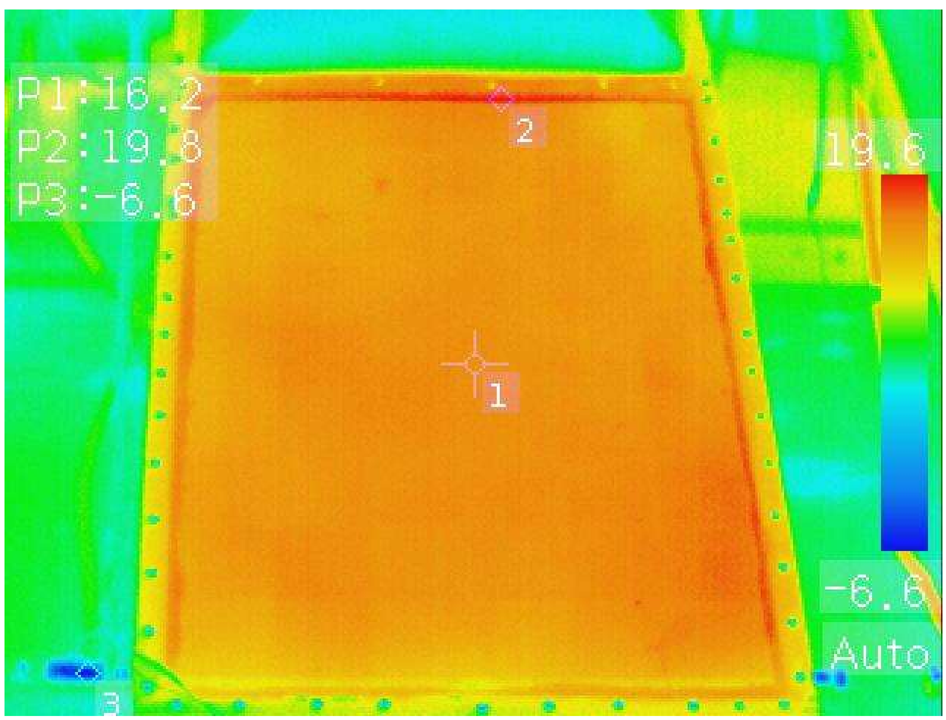

Figure 4. 20: PVT collector temperature by thermal imaging camera. (17 Feb.), at (12:55 PM)

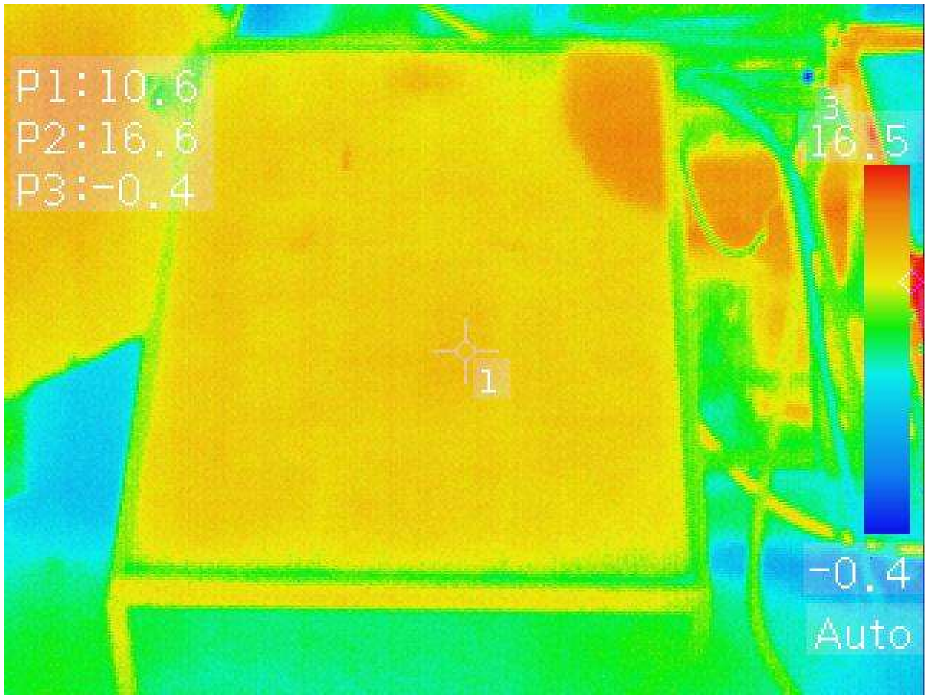

Figure 4. 21: PV panel temperature by thermal imaging camera. (17 Feb.), at (12:55 PM)

In table (4.5), one of the main reasons of the difference between the inlet water temperature in conventional thermal collector and PVT collector is that the water entered in the two collectors was stored in separate storage tank in the previous day after being heated through the water cycle in two collectors. This of course will show its effect on the temperature of outlet water (T_o) from both collector. But when calculate the different between inlet and outlet water for both, can see that the value is close together. By using equation (2) to calculate the thermal efficiency, can see in PVT and thermal collector that the thermal efficiency is near together.

Table 4. 5: Data collected at different dates and times, to calculate η_{th} depend on T_i and T_o for two collectors at the same T_a and G

Date	Time (h)	Amb. Tem.(ºC)	Radiation (G) (W/m²)	Ti (ºC)		To (ºC)		η_{th} (%)	
				Thermal coll.	PVT coll.	Thermal coll.	PVT coll.	Thermal coll.	PVT coll.
24 Feb.	14:23 PM	21	632	48	20	60	31	0.85	0.85
6 Mar.	13:26 PM	19	849	28	17	41	27	0.82	0.83
12 Mar.	13:25 PM	24	602	46	23	57	34	0.87	0.87
9 Apr.	13:40 PM	28	882	38	26	53	38	0.85	0.85
11 Apr.	14:00 PM	24	883	43	27	58	38	0.84	0.84

Chapter 5

5. Conclusions and Recommendations

5.1. Conclusions:

Hybrid photovoltaic thermal collector design has been designed in this thesis. The main intention was to design a hybrid collector and electric PV system with high productivity with high efficiency. The proposed system can perform the integrated function instead of two separate systems, one electric and the other thermal. It also has the compatibility in installation with building, insulating, structural stability. The studying of advancements in photovoltaic thermal collector has been done, some of the features that were designed, and some of their properties, were reviewed, and the most consistent and architecturally integrated design was identified where is it competitive and cost-effective. The best option among the several module found in the review is flat plate, this design is suitable for buildings, and its cost is appropriate, and there is great possibility of modification and build the new system on it.

The collector is designed to be suitable for installation on the roof using easy structure, and is combined the PV panel with thermal collector. Parallel pipes were used under the PV panel so that water passes through them. Paraffin wax was added between the panel and the pipes so that the pipes were surrounded by all the sides, to keep the heat inside the collector. The PV panel covered two-thirds of the top surface of the collector while the third one remained a thermal side.

The analysis has been made on collector parameters, as thermal and electrical efficiency, fill factor, maximum power point, and open circuit voltage and short circuit current, inlet and outlet water from the collector, temperature of paraffin wax inside the PVT collector, the effect on I-V and P-V curve.

Results show that the thermal efficiency of both collectors is very close to each other. Although the conventional thermal collector in sunny days has a high water temperature of up to (50 ^{O}C), the difference between the inside and outside water temperature of both collectors is almost equal. But in a non-clear days, and with a solar radiation of no more than (250 W/m^2), the inlet and outlet water temperatures in both are close together. The electric efficiency of PV_{CO} and PV_{PVT} reached a good ratio exceeding (9%), by the amount of electrical energy generated by them at different solar radiation values. Electrical efficiency was affected by high solar radiation values exceeding (850 W/m^2) due to the high temperature of the PV cells. This effect was shown on the I-V curve, where the V_{OC} decreased with a slight rise in the I_{SC}. The PV_{PVT} produced a good amount of electrical energy that varied depending on the amount of solar radiation reaching it. Sometimes up to (95 W) at solar radiation exceeding (850 W/m^2). This energy can be used to operate electric heaters that heat the water in the tank at the need. The temperature of the PV_{PVT} was higher than that of the conventional PV panel, especially at high solar radiation. The conventional PV panel was exposed to the air which was continuously cooling the panel, while the PV_{PVT} was put it directly to the paraffin wax, which also surrounded the pipes. The increase temperature of, PV_{CO}, PV_{PVT}, outlet water, and paraffin wax, effect by the increase in solar radiation, where with rise solar radiation the temperature of this parameters rise steadily.

One of the most important features of the integrated PVT collector is that we can get thermal and electric energy at the same time, and by using the same space. It's more effective than building two separate systems, one electric and another thermal, which means doubling cost, and will be the need for larger areas.

5.2. Recommendations:

- In the experiment performed, it was not possible to evaluate the effect of the thickness of the appropriate paraffin wax material below the PV panel to allow a greater transfer of heat from the bottom of the panel to the pipes and from it to water. Thus, it is recommended that the thickness of the paraffin wax under the panel must be observed.

- In the experiment performed, there is no work to increase the thermal conductivity of paraffin wax, so it is recommended in the case of a similar model, to increase the thermal conductivity of paraffin wax to transfer the heat from the bottom of the panel to water inside the tubes.

- We recommend to build the following models and make a comparative study between them, to be identified which one is more efficient and effective than the other:

  1 - The same specifications of the model presented in the study, but the PV panel must be comprehensive surface.

  2 - The design is done as in the figure shown:

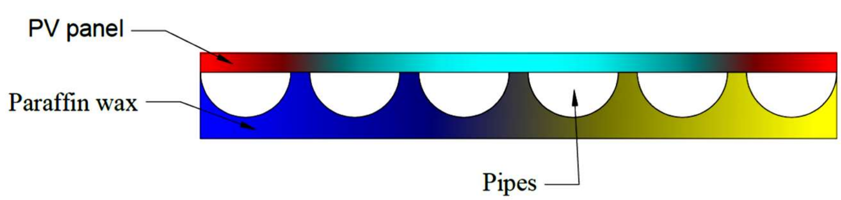

Figure 5. 1: Proposed new design of PVT collector.

- We recommend that if the model presented in figure (5.1) is constructed, it should be studied with a single, double glass cover or without it.

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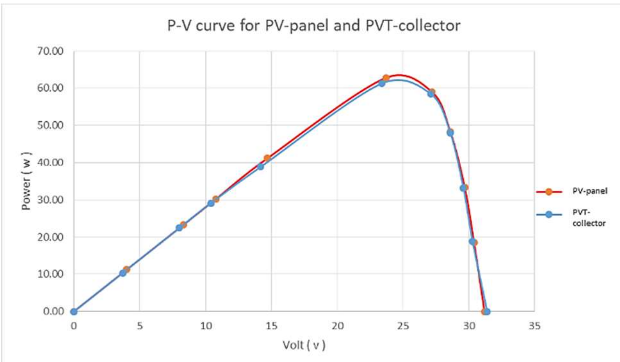
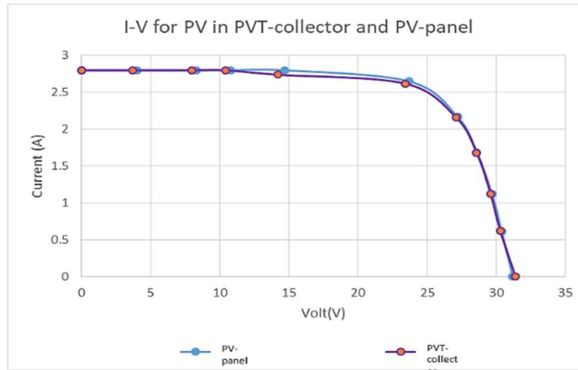
APPENDICES

Appendix A

I-V and P-V Curve (in Feb. and Mar. and Apr.)

21/ Feb. at 9:00 AM





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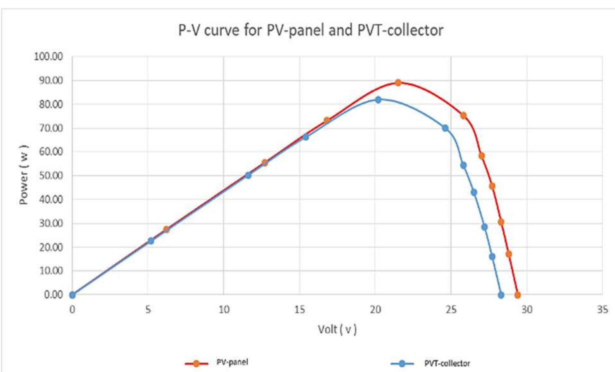

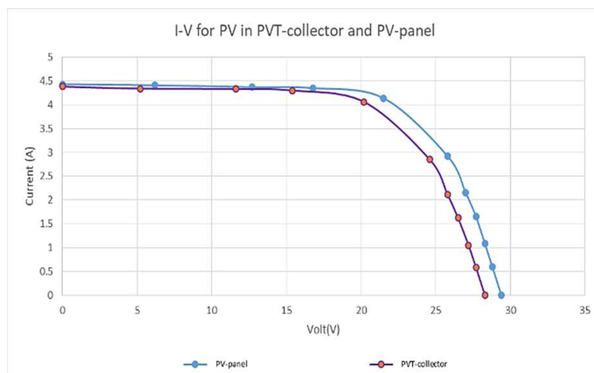

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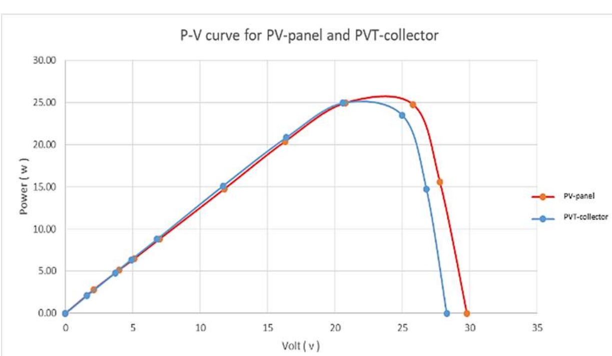
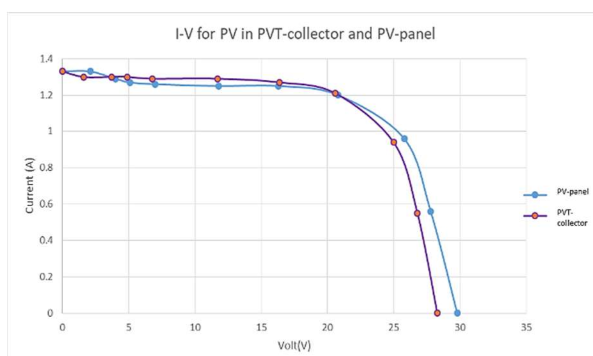
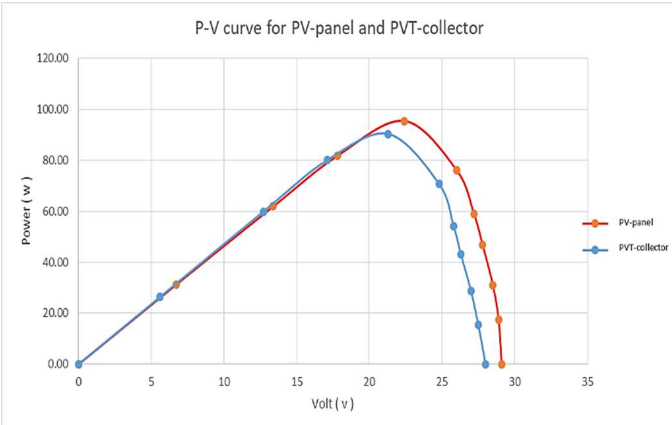
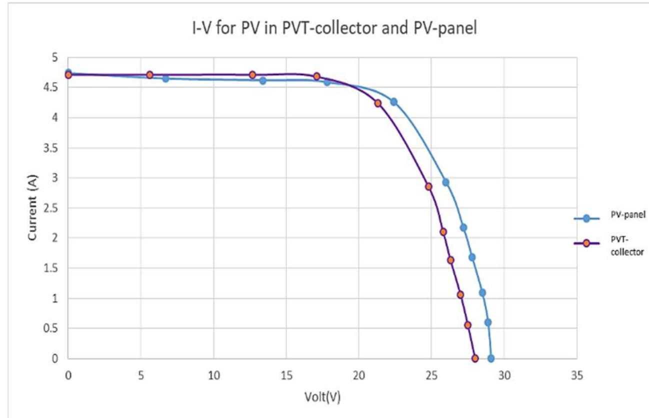


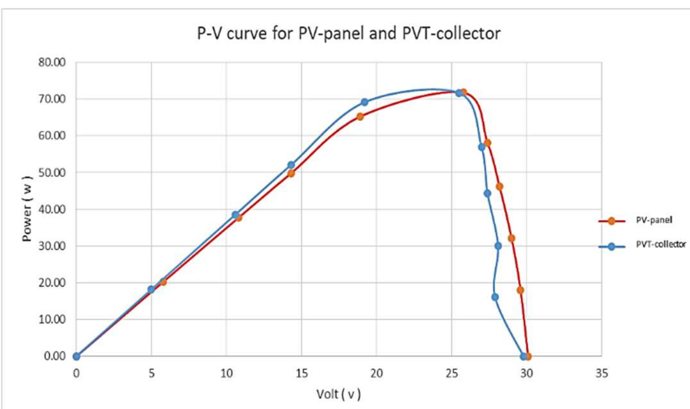


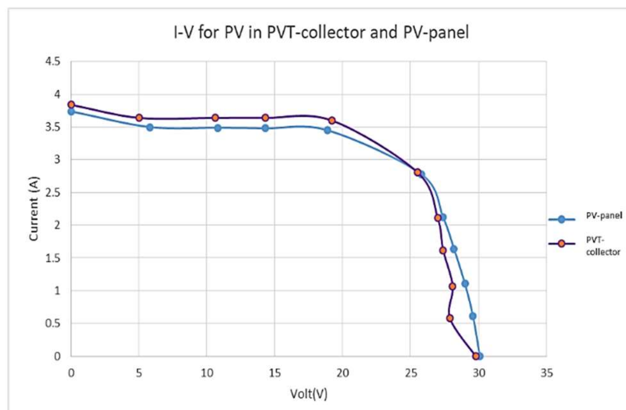
11/ Mar. at 13:30 PM



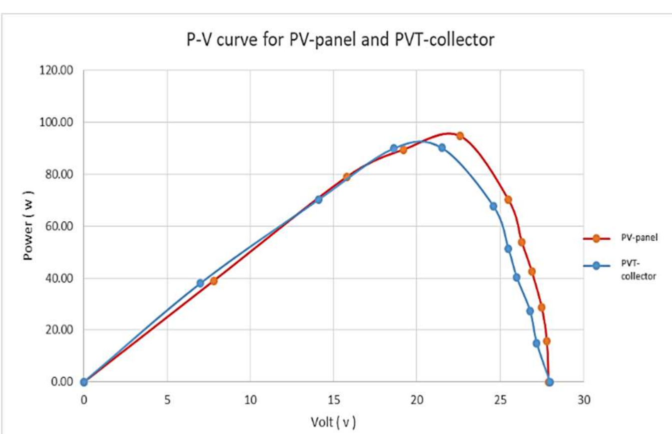


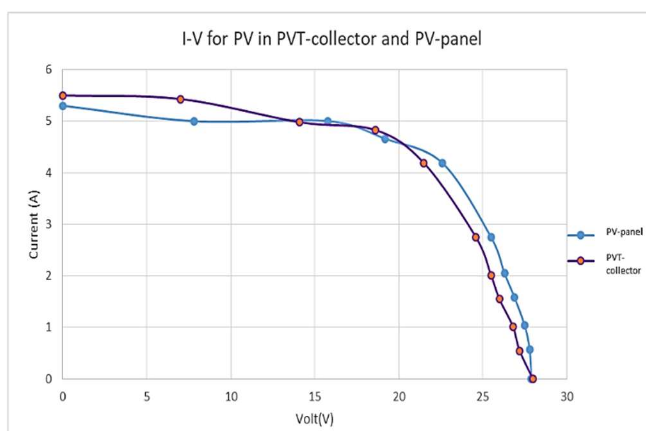
4/ Apr. at 10:00 AM





4/ Apr. at 12:35 PM





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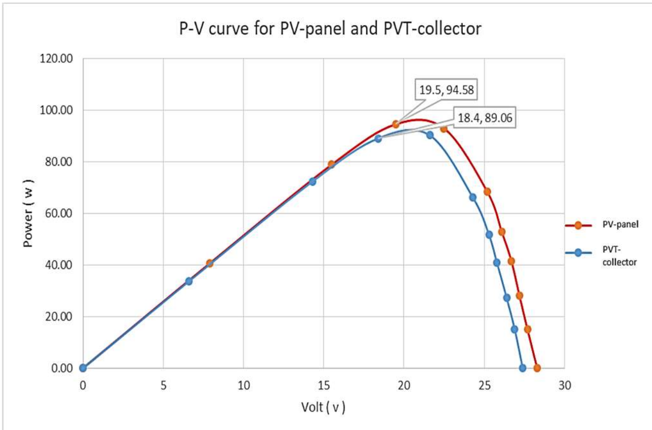
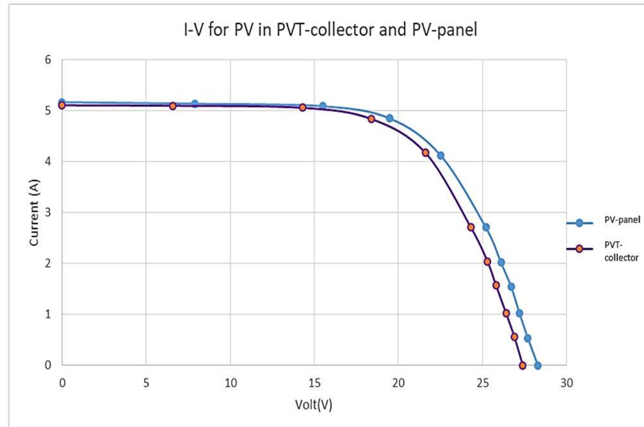
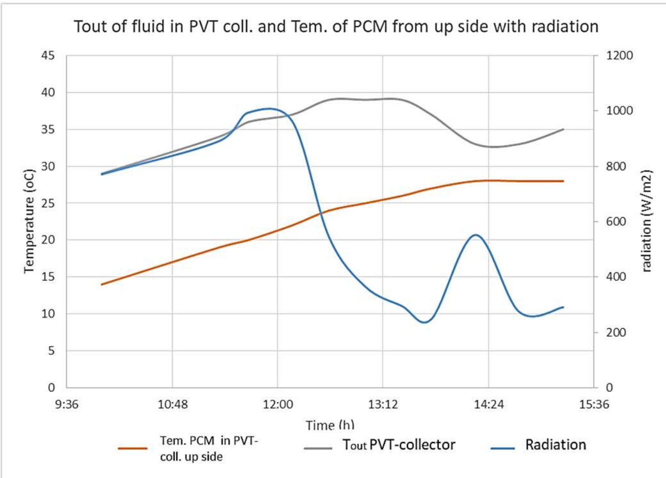


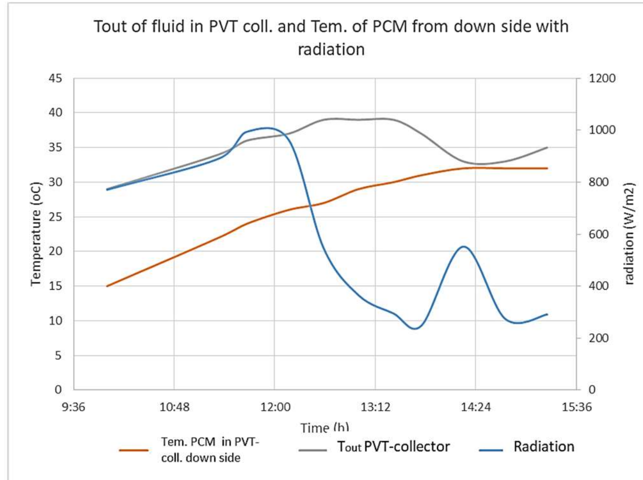


Appendix B

Relation between radiation and outlet water and PCM (upside and down side) in PVT.

4/ Apr.





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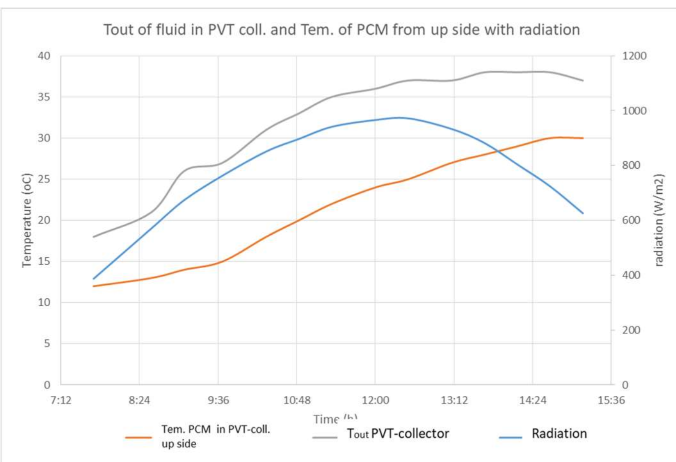

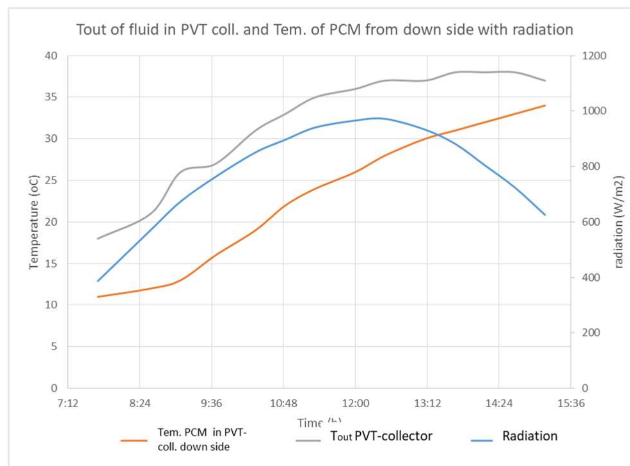

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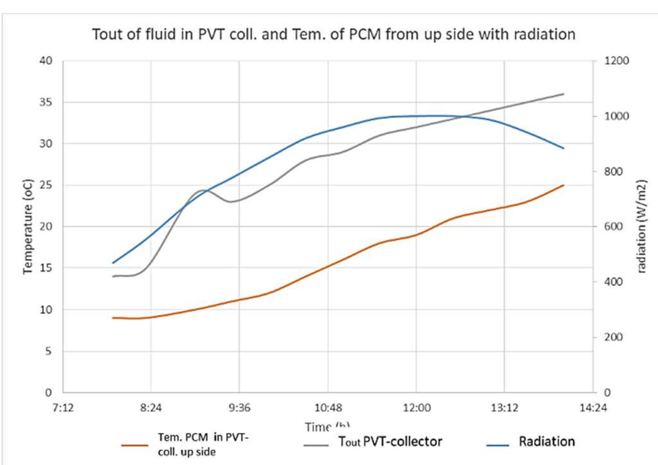
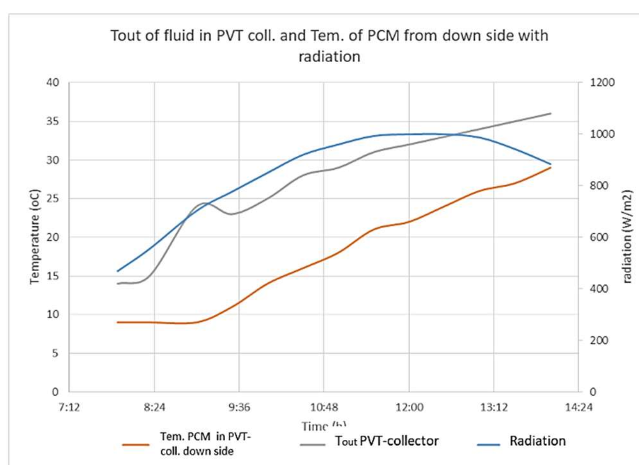
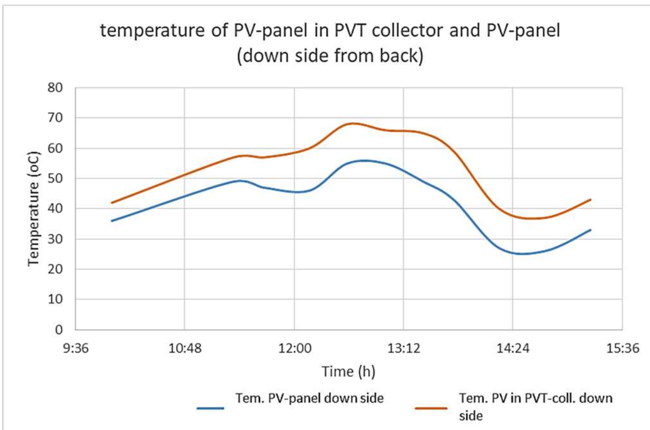


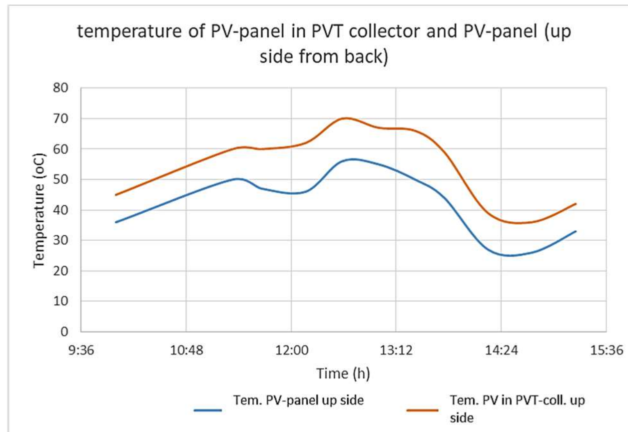


Appendix C

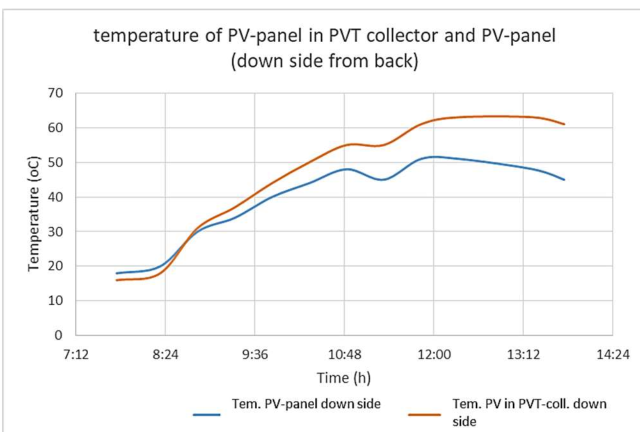
Relation between temperature of PV-panel in PVT collector and PV-panel (upside and down side from back).

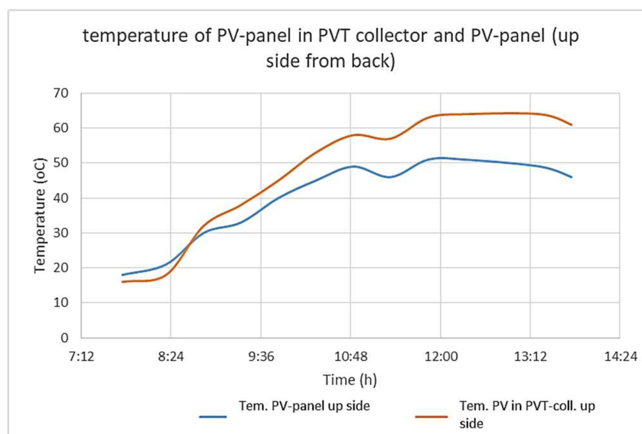
4 / Apr.



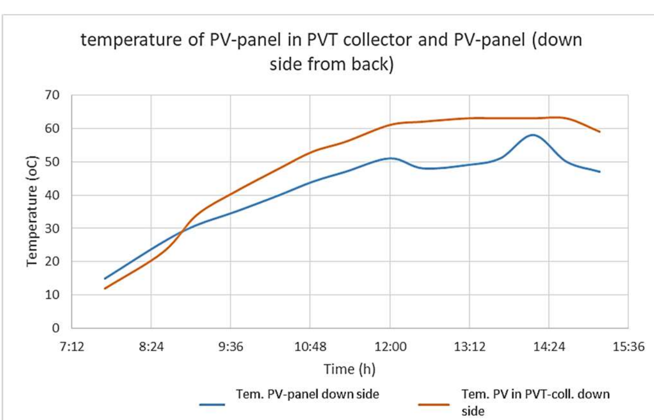


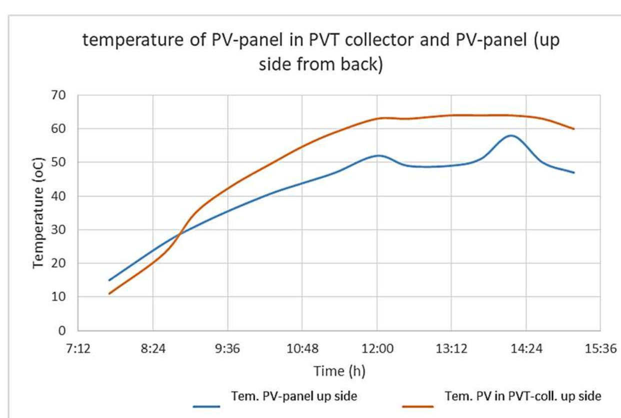
8 / Apr.





9 / Apr.

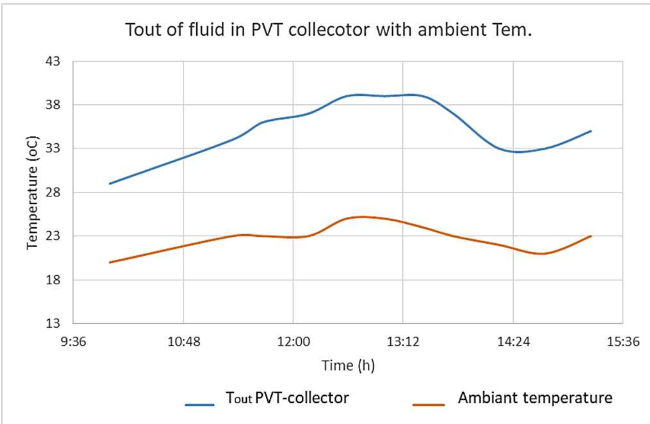


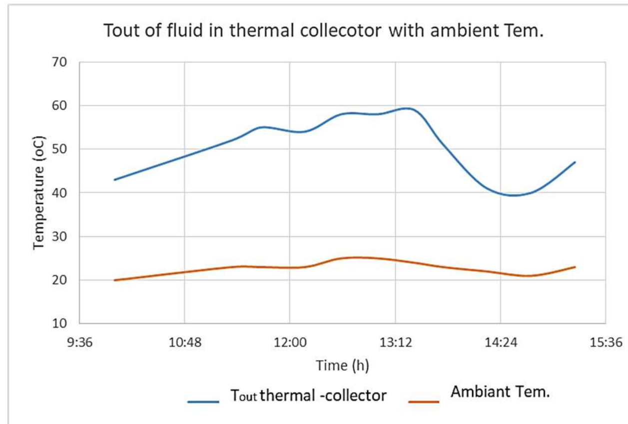


Appendix D

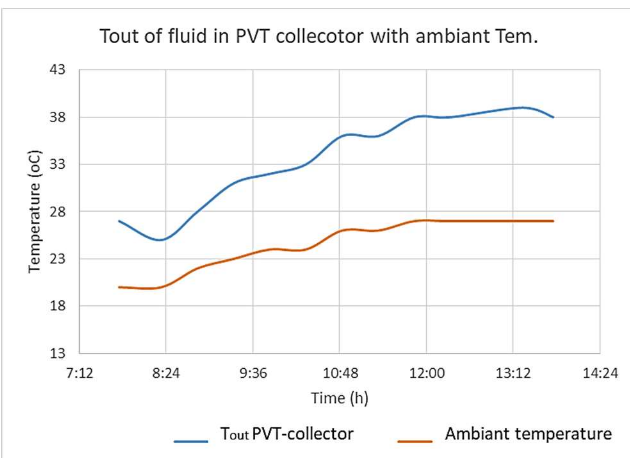
Relation between outlet water temperatures in PVT collector and in thermal collector with ambient Tem.

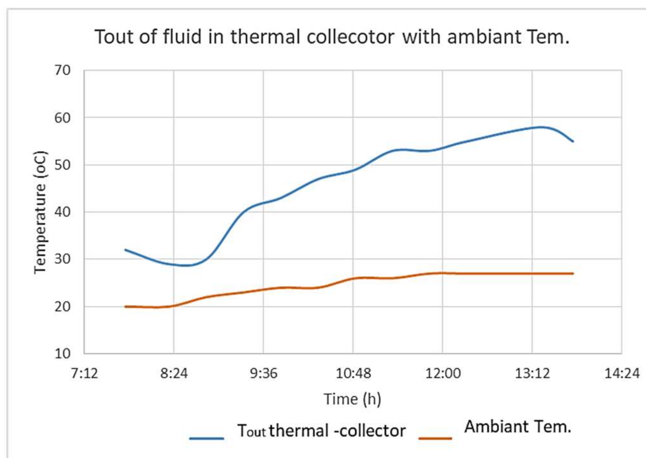
4 / Apr.





8 / Apr.





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