An Experimental Investigation of a Concentrating PVT Systems

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ABSTRACT

Solar Photovoltaic (PV) systems harness the solar energy from the sun and converts it into electrical energy. The electrical efficiency of a PV system depends on the type of cells, and the working temperature of the system. The efficiency of a PV module decreases as its temperature increases due to incoming solar radiation. Even with the decreasing cost of the PV modules, the efficiency is still low due to the above mentioned factors (ideal conversion efficiency is about 15%) and most of the radiation reaching to the PV modules is wasted as heat. Therefore, there is a need to remove or better still utilize this waste energy. The Photovoltaic- thermal system (PV/T) is a hybrid system that produces thermal energy as well as electrical energy.

This thesis experimentally investigates the use of solar concentrated photovoltaic-thermal system (CPV/T) to boost the overall productivity of the solar PV module. In CPV systems mirrors or lenses are used to concentrate sunlight onto solar cells. High-efficiency solar cells are used in CPV systems where concentration ratios are high but conventional solar cells can be used at low concentration ratios (i.e., less than 10). The studied CPV/T system uses mirrors to intensify the solar radiation on the PV module of about 3 times. The performance of the CPV/T collector was analyzed and compared to that of the reference PV module working under the same weather conditions of the Northern Cyprus in the month of June. The CPV/T system was established by attaching a set of 4 mirrors to the module frame and a glass duct mounted on the top of the module for cooling purpose. With Water used as the coolant and heat carrier.

The inlet temperature of the coolant was varied between 14 ^{o}C and the ambient temperature (i.e., 14°C, 18°C, 22°C and ambient temperature). In this experimental work, it was found that the CPV/T collector performed better using an inlet cooling water temperature of 14°C. The maximum electrical power output from the CPV/T system was 49.06 W yielding a 3.3 times the rated power of the PV (15 W at STC), and its maximum thermal output was 920 Wh/m^{2}.

Keywords: Photovoltaic, CPV/T collector, Electrical power, Thermal energy.

ÖZ

Solar Fotovoltaik (FV) sistemleri güneş enerjisini elektrik enerjisine dönüştürür. FV sisteminin elektrik verimililiği güneş pilinin tipine ve sistemin çalışma sıcaklığına bağlıdır. FV modülünün sıcaklığı, gelen güneş ışınlarının nedeniyle arttıkça verimliliği azalır. FV modüllerinin maliyetleri azlsa bile yukarıda belirtilen faktörlerden dolayı verimlilikleri hala düşüktür (ideal dönüşüm verimliliği yaklaşık %15) ve FV modülüne ulaşan radyasyonun çoğu ısı olarak heba olmaktadır. Bu nedenle, atık ısıyı uzaklaştırmak ya da daha iyisi kullanmaya ihtiyaç duyulmaktadır. Fotovoltaik-termal sistemi (PV/T) ısı enerjisi ve elektrik enerjisi üreten bir hibrid sistemdir.

Bu tezde FV sisteminin genel verimliliğini artırmak için konsantre fotovoltaik-termal sistemin (KFV/T) kullanımı deneysel olarak araştırılmıştır. KFV sistemlerinde aynalar veya lensler güneş hücreleri üzerine güneş ışığı konsantre etmek için kullanılır. Yüksek konsantrasyonlu KFV sistemlerde yüksek-verimli piller kullanılır, ancak düşük konsantrasyonlu KFV sistemlerde geleneksel piller kullanılabilir (örneğin 10 dan az konsantrasyon oranı). İncelenen KFV/T sisteminde aynalar kullanılarak güneş ışınları FV modülüne yansıtılmış ve ışınımlar 3 kat artırılmıştır. KFV/T kolektörün performans analizi haziran ayında Kuzey Kıbrıs Türk Cumhuriyeti-Mağusa'da, aynı hava koşullarında çalışan referans FV modülü ile karşılaştırılmıştır. Bir FV modül çerçevesine 4 ayna takılmış ve modülün ön yüzeyine soğutma amaçlı cam kanal monte edilerek KFV/T sistemi oluşturuldu. Soğutucu ve ısı taşıyıcı olarak su kullanıldı.

Soğutma sıvısının giriş sıcaklığı 14^{o} C ile ortam sıcaklığı arasında (örneğin, 14 ° C, 18 ° C, 22 °C ve ortam sıcaklığı) değiştirildi. Deneysel çalışmada KFV/T kolektöründe en iyi verimlilik soğutucu sıvı giriş sıcaklığı 14 ^{o}C olduğu zaman elde edildi. KFV/T sistemde elde edilen maksimum güç FV modülünün nominal gücünün (15 W) 3.3 katı olarak (49.06 W) elde edildi, ayrıca elde edilen ısı 920 Wh/m^{2} olarak bulundu.

Anahtar Kelimeler: Fotovoltaik, KFV/T toplayıcı, Elektrik gücü, termal enerji.

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$(\alpha\tau)_{eff}$	Product of the effective absorptivity and transmittivity
η_e	Electrical efficiency (%)
η_{max}	Maximum efficiency (%)
η_{th}	Thermal efficiency (%)
C_p	Specific heat capacity of water (J/Kg.°C)
$F^{'}$	Flat plate collector efficiency
G	Solar Irradiance (W/m²)
h_{p1}	correction factor due to the PV cell material, glass, and EVA
I	Current (A)
L	Length of the CPV/T water collector(m)
$\dot{m}$	Mass flow rate (Kg/s)
P	Power (W)
Q_U	Useful thermal energy (W)
T	Temperature (°C)
T_{amb}	Ambient temperature (°C)
T_{cell}	Temperature of the PV cell (°C)
T_{in}	Inlet temperature of the coolant (°C)
T_{out}	Outlet temperature of the coolant (°C)
U_{tT}	Overall heat transfer coefficient from the solar cell to the coolant(W/m².K)
U_L	Overall thermal loss coefficient (W/m². K)
V	Voltage (V)
W	Width of CPV/T water collector (m)

W	Watt

Chapter 1

1 INTRODUCTION

Solar photovoltaics (PV) are quite an old technology, that has been studied and used since the early 19th century. But it is gaining increasing attention today because of the present difficulties facing the Fossil fuel energy and the increasing concerns about the impact of the fossil fuel on the environment.

Several renewable and alternative forms of energy exist today and while some are in full scale production practice while many others are still within the experimental stages. Examples of forms of energy include: wind energy, nuclear energy, biomass, geothermal, hydro, solar, etc. while most of these hold good promise, caution must be given to the environmental impact of any of these energies for the future. This is because the increasing energy demand puts a huge pressure to increase production of energy, but some factors should be taken into consideration as we live in a time when sustainability is no longer a debate but a necessity;

1) The petroleum reserve of the world is being depleted, and we don’t have enough to meet the projected energy demand.
2) The waste of these old forms of energy is contributing greatly to the destruction of our planet, and it is at an irreparable state as the emission of greenhouse gases continues to rise and leading to things like global warming, the rise of sea levels, air and water pollution which depreciates the health condition of humans.

3) Petroleum has been for years, the cause of many international and internal conflicts, and with the reduction in reserve, the struggle for ownership and control would lead to bigger conflicts.

For these and many more reasons, we must seek better alternatives which are called Green energy sources. Of all green energy sources, solar has been the most successful and progressive, with it’s use ranging from electricity production, air and water heating, food processing, to water desalination processes and many more uses with unlimited sources from the sun.

The reality is that the amount of energy gotten from through solar only depends on our technological advancements rather than on the energy reserve of the sun. Several solar technologies have been developed and in use today of which solar thermal collector and solar PV systems are the most advanced and widely used.

1.1 The PV system

The solar energy received from the sun cannot be directly used unless converted to either thermal, electrical or any other form of useful energy. In electricity production, the solar energy is converted in a semiconductor device called a solar cell. A series of solar cells are connected together to form a solar panel in order to produce useful amounts of voltage or current, and for large scale production, multiple solar panels are assembled to form a solar array, as shown in the Figure 1 below.

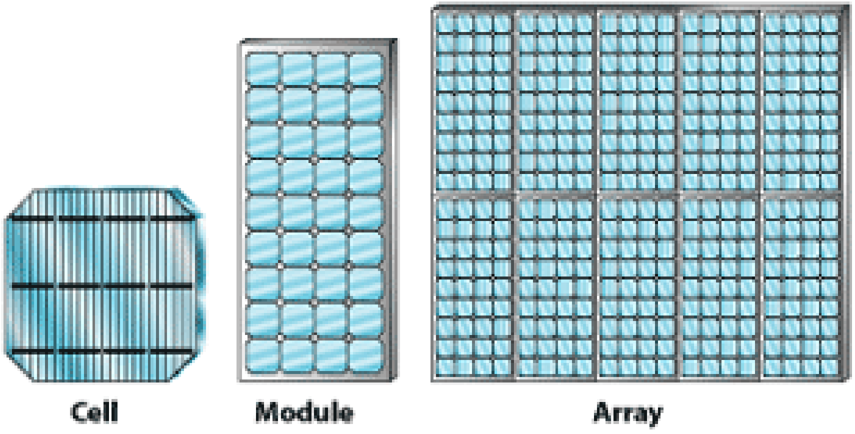

Figure 1: Solar PV cell, module and array[1]

In order to have a complete PV solar System, there are a number of components added to the system, like;

- ✓ Mounting frames to which PV panels are attached and positioned to receive the solar radiation from the sun.
- ✓ Storage unit is of essence as the sun does not shine at night. The popular storage unit is the battery system.
- ✓ Charge regulators conditions the panel’s output, DC (direct current) and delivers it to the battery, grid or appliances.
- ✓ Inverters are required to convert DC to AC (alternating current).
- ✓ Balance of system (BOS).
- ✓ Finally, the household electrical load.

Figure 2 shows the schematic diagram of these components

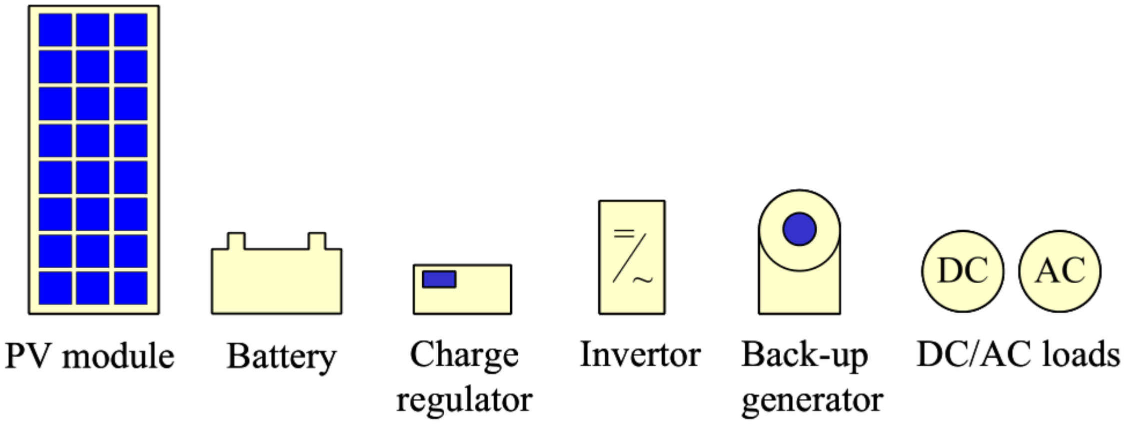

Figure 2: Components of a solar PV system[2]

1.2 Photovoltaic-thermal system (PV/T)

The use of the solar PV takes one step ahead in what is called the PV-Thermal (PV/T) system, which is a solar PV that is used to produce thermal energy as well as the electrical output. This hybrid form of the solar PV use increases the overall efficiency of the system, as the increased temperature which reduces the electrical performance of the PV module is extracted as useful thermal energy, thereby cooling the PV module and producing another form of desired energy.

The two main drivers for this system are; the need for thermal energy and also cooling of the PV panels as their efficiency drops with increasing temperatures. The PV/T systems come in two main forms, PV/T air, in which case air is used as the cooling fluid and PV/T liquid, where water is used as the coolant.

Although the overall performance is improved in the PV/T, the electrical output is still low, therefore, to raise the electrical yield of the PV/T system, reflectors are used to concentrate sunlight onto the solar PV/T collector, this is done because the electrical output depends on the amount of sunlight absorbed by the PV cell, so the concentration would increase the sunlight focused on the PV/T module as well as increase the thermal output.

1.3 Aim

The goal of this work is to investigate the electrical and thermal output of a CPV/T collector. A low CPV/T was erected with water as the cooling fluid, running over the surface of the CPV/T collector. A set of four plain mirrors were used and attached to the CPV/T system. The experimental outputs were compared to those of a reference PV module.

1.4 Motivation

Several factors motivated this study, which includes:

1) The high cost of installing a PV/T system and the desire to increase the performance of a single PV/T collector by the use of simple reflectors.
2) The limitation of space usage for the installation of solar PV/T collectors

1.5 Thesis outline

The outline of this study is as follows:

- Chapter 1 gives the introduction to the study
- Chapter 2 is the literature review of previous studies done in the field of solar PV/T and CPV/T collectors.
- Chapter 3 deals with the design of the CPV/T collector and some introduction to the numerical analysis of the electrical and thermal performance of the collector.
- Chapter 4 contains the experimental setup and procedures
- Chapter 5 The results are analyzed and discussed in details.

- Chapter 6 presents the economic analysis of the PV and CPV/T systems using the Life Cycle Cost Analysis
- Chapter 7 presents the conclusion with some suggestions for future work.

Chapter 2

2 LITERATURE REVIEW

Several research and experimental work in several countries have been done to investigate the different configurations of the PV/T and also on the CPV/T, and all has been because of the desire to better utilize the solar energy in providing electricity and thermal energy as well as improve on design to make the system cost effective and aesthetically appealing.

The hybrid PV/T systems have been long experimented and researched on, research works as earily as those of Wolf et al.[3], Florschuetz et al. [4], Kern et al.[5] and Hendrie et al.[6] of th 1970s established the basic and initial concept of PV/T, making use of either water or air as cooling fluid (i.e. the PVT/w for water and PVT/a for air systems in abbreviation). Following these, many research work primarily on flat-plate collectors started with great contributions to the field, such of the works include those of Raghuraman et al. [7], Cox et al.[8] Braunstein et al.[9] of the 1980's. Concentrated PVT system was investigated in the works of O'leary et al.[10], Mbewe et al.[11], Hamdy et al.[12]. Garg et al. [13][14][15][16] in his work did an extensive analytical and experimental study on hybrid PV/T air and liquid heating systems.

More recent research studies on the use of Photovoltaic thermal for water heating system for residential purpose, Chow et al.[17] stated that the fin efficiency and the bonding quality have great impact on the overall efficiency of a PV/T collector. Using a single-glazing flat box type collector he covered the surface of the collector with PV modules and obtained the following result, 57.4% for the thermal efficiency and 11.5% for the electrical efficiency.

Erdil et al.[18] designed a hybrid PV/T system using two PVmodules, eachh 0.6m² in Cyprus and measured a total of about 2.8kWh of thermal energy daily, but reported significant losses in the electrical energy due to system design of about 11.5%

Bingqing et al.[19] found impressing results using a novel tile-shaped dual-function solar collector which compared to the conventional dual function collector yielded an instantaneous efficiency of 53.2% - 69.1% and a standardized instantaneous efficiency othe semicircle cover collectoror is 67.9% comparedre to the conventional daily efficiency of the dual function collector of 44.7% - 59.2% and standardized instantaneous efficiency of 54.1%.

A study on low concentrating PV/T systems was done by Rosell et al. [20] using a linear Fresneconcentratorrs with a channel PV/T collector, the work majored on the thermal output of the collector which gave thermal efficiency of above 60%.

Coventry et al.[21] designed the CHAPS (combined heat and power solar) PV/T collector, which yielded thermal efficiency of about 58% and electrical efficiency of 11% using a parabolic trough with a concentration ratio of 37 times with monocrystalline silicon cells and also a two-axis tracking system.

Researchers have also investigated the effect of the mass flow rate of the cooling fluid on the efficiencies of the PV/T, but still have not agreed on a common optimum flow rate. Significant works include those of, Chow et al.[22] who reported that as the flow rate rises from 0.002 to 0.016kg/s, there is also a growth in the thermal and electrical efficiencies.

A careful look at the different views of different researchers, such as Bergen et al.[23], Morita et al.[24], Adnan et al.[25] suggests that the optimum flow rate is between 0.001 – 0.008kg/s m^2, however, flow rates of 0.015kg/s m^2 was also reported by Garg et al.[16].

With impressive success reports from the use of single fluid hybrid systems Abu Bakar et al.[26] designed an improved PV/T collector with bi-fluid configuration, with flow rates fixed at 0.06 kg/s and 0.02 kg/s for air and water respectively, reported improvedefficienciess. The overall performance of the collector was improved by almost 14% with the addition of the cross corrugated air channel

In the case of the Building integrated PV, Taylor et al. [27] investigated the use of forced air in cooling, anits's impact of the combined performance of the PV. In his experiment, electrical power output was increased by 0.4%/1°C. Also, Tripanagnostopoulos et al.[28] in his work established that using air rather than water for PV cooling was cheaper, but it has a lower efficiency in electrical and thermal performance. He also used forced air flow which increases the thermal output, but the electrical efficiency was reduced due to the electrical input by the fan.

Tingting et al.[29] Showed in his work that the application of two – inlets in the building integrated systems, increases the thermal efficiency by up to 5% and it has a marginal impact on the electrical efficiency as well.

Chapter 3

3 THE DESIGN OF CPV/T COLLECTOR

3.1 Introduction

Several factors affect the electrical efficiency of the solar PV system, the amount of solar radiation that hits the surface, the absorbent quality of the PV cells, and the working temperature of the cells.

Improvements to the PV cell materials are ongoing and some new materials have been introduced with improved efficiency, such as;

- Amorphous (a-Si) and micromorph silicon (a-Si/μc-Si);
- Cadmium-Telluride (CdTe); and
- Copper-Indium-Selenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS).

The introduction of the PV/T system reduces the effect of the working temperature as a temperature rise of the panel as low as 1°C rise causes a 0.5% decrease of the electrical efficiency, the PV/T systems not only reduces the temperature but converts it to useful thermal energy which increasing the overall efficiency of the system.

But the problem of the amount of solar radiation on the PV cell, area of the PV cell and a number of the PV cells, would all be solved by the used of the concentrated PV/T (CPV/T) which uses cheap reflectors, such as mirrors to increase the solar radiation on the panel, and this increases both the electrical and thermal efficiency of the system.

Several research works have shown that using either air or water as the coolant in the CPV/T increases the overall efficiency, but more to this is the reduced cost, as using mirrors lead to higher productivity from just one panel.

3.2 Structure of CPV/T collector

In this study, two 15W PV panels were used, having an efficiency of 10.9% each, see Figure 3 below. The specifications are considered at Standard Test Conditions (STC) with the solar intensity G=1000 W/m², mass of air=1.5 and Temperature T=25°C, see Table 1 below.

Table 1: Specifications of each PV panel

PV panel variables	**Value**
Panel brand	Euro plus solar DS-A1-15
Peak power (P_{max})	15 W
Voltage at P_{max} (V_{mp})	17.3 V
Current at P_{max} (I_{mp})	0.87 A
Open circuit voltage (V_{OC})	21.6 V
Short circuit current (I_{sc})	0.96 A
Power tolerance	±5%
Area of the panel	390x350 mm²
Thickness	25 mm
Weight	1.8 Kg

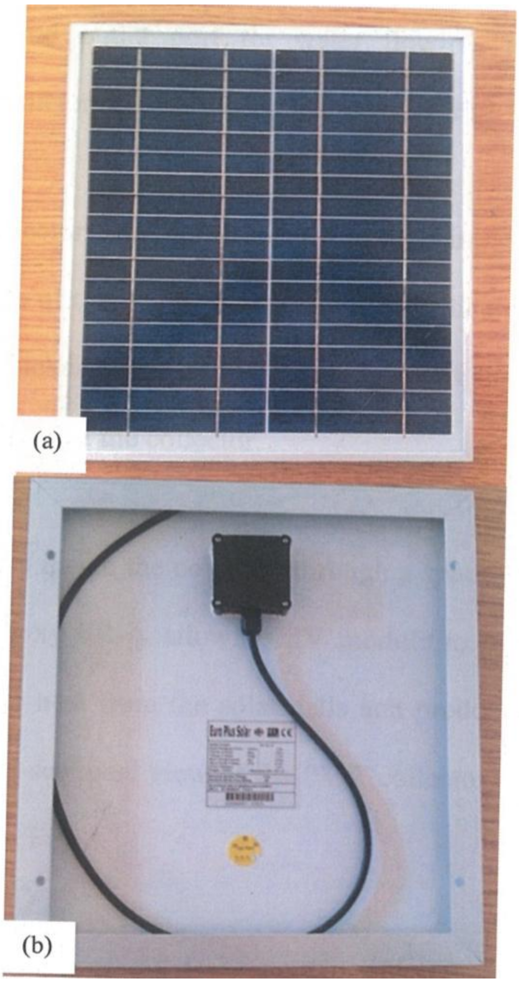

Figure 3: The PV panel (a) front view; (b) The back view with the junction box

The panel is a combination of PV cells and Ethylene-vinyl acetate (EVA) encapsulated between a glass sheet on top and a tedlar film for the backside.

The Hybrid PV/T was designed with the cooling water channel on top of the PV panel, see Figure 4 below.

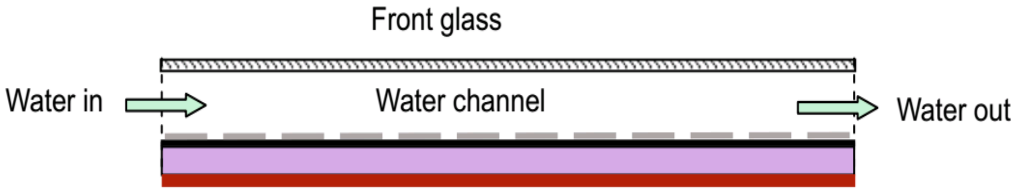

Figure 4: Channel above the PV Panel [28]

The panel's front surface was covered with a casing made of transparent glass, and after several tests an optimum height of the glass covering was reached to 12 mm from the surface of the PV panel, this was done to reduce the energy loss due to reflections from the water, which could reduce the electrical efficiency of the system, but high enough to allow proper heat transfer from the PV to the water. The glass covering was built with inlet and outlet for the water and seal on the PV with transparent silicone adhesive sealant, see Figure 5 below.

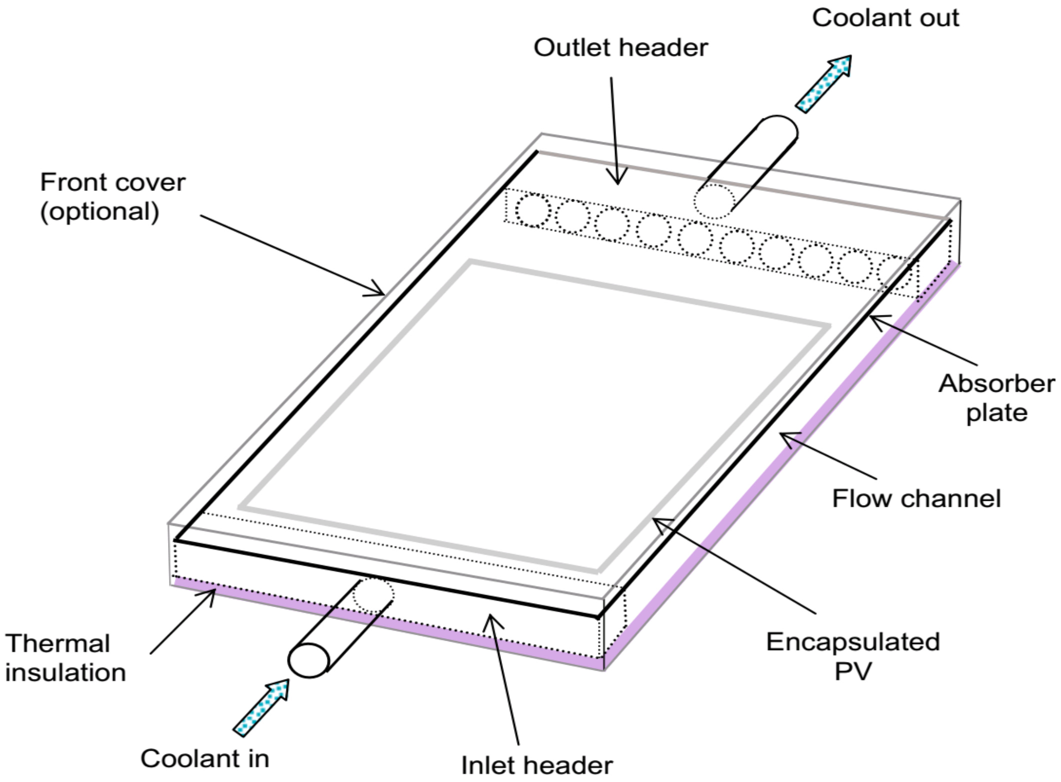

Figure 5: A schematic diagram of the PV/T panel [28]

The entire frame of the Hybrid PV/T was attached to a 290 mm metal pipe as shown in Figure 6 below and a T-shaped metal pipe of length 1850 mm was used to suspend the system, see Figure 7 below.

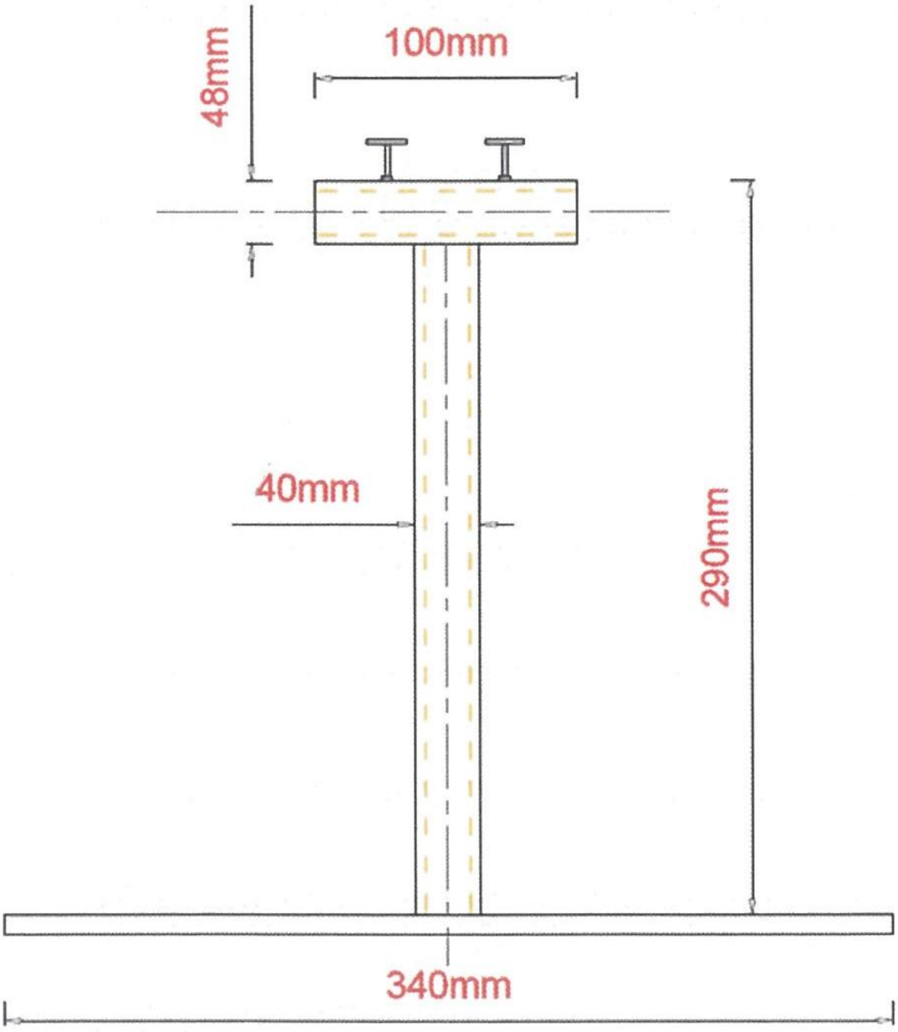

Figure 6: metal pipe attached to the PV Panel frame

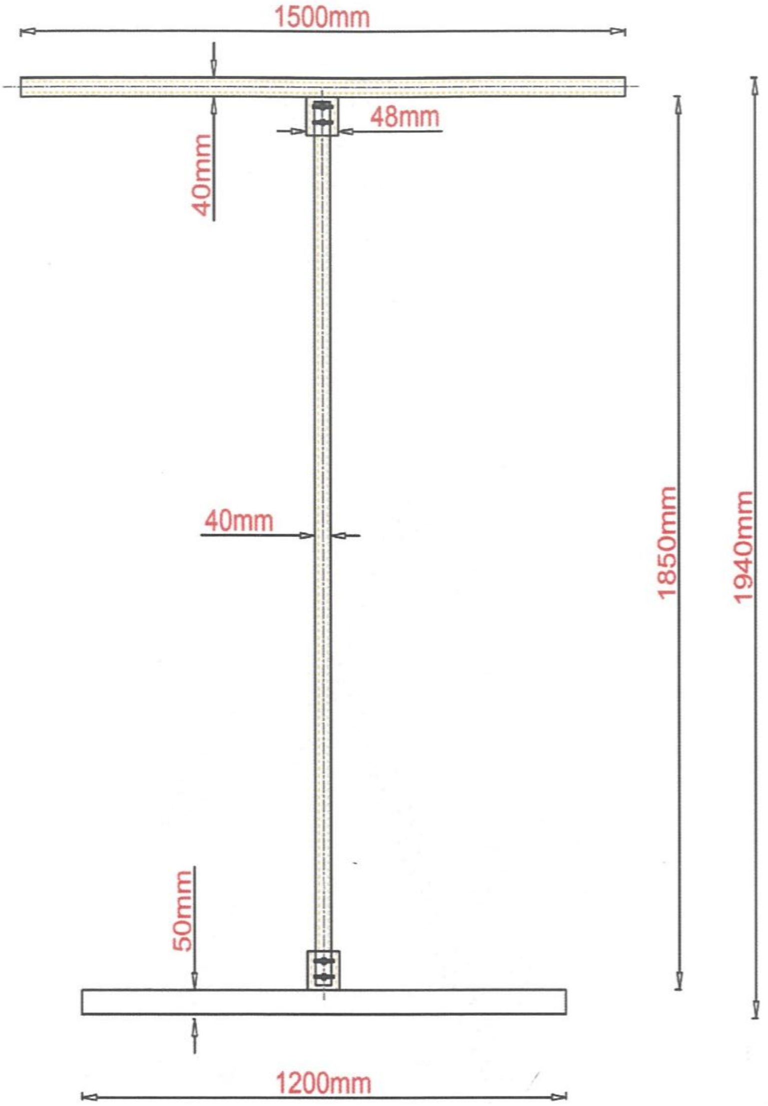

Figure 7: Metal pipe for holding up the PV panel

The Figure 8 shows the top view the backside of the PV and the cross section of the PV panel.

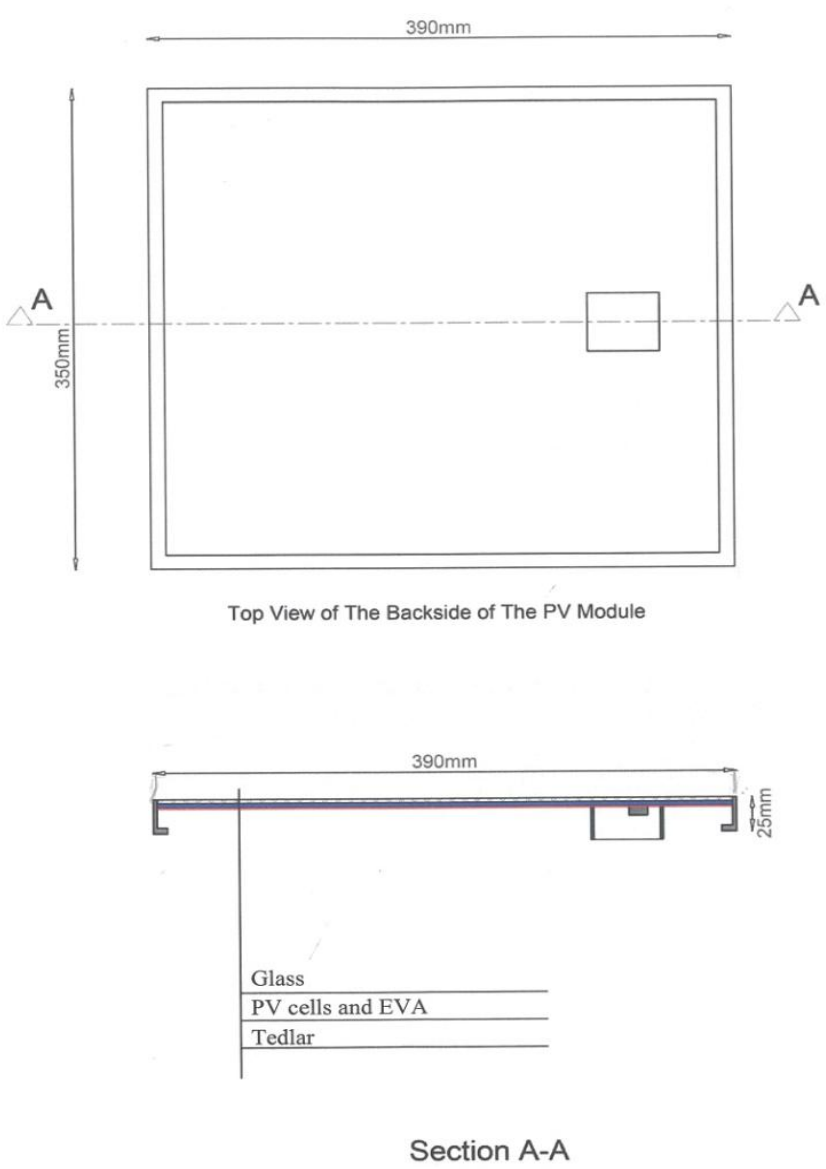

Figure 8: The top view of the backside and the cross section

The CPV/T system was done by the use of plain flat mirrors attached to the frame of the PV/T panel at an angle of $\theta = 60°$ with dimensions 390x500 mm. The angles were calculated using the formula (3.1) and (3.2), (as illustrated in Figure 9 below), this enables the reflections of the mirror to cover the entire PV surface [30];

$$Inner\_angle = 90° + \sin^{-1}\left(\frac{-reflector\_length}{4xtarget\_width} + \sqrt[\frac{1}{4}]{\frac{reflector\_length^{2}}{target\_width^{2}} + 8}\right) \tag{3.1}$$

$$\text{Outer\_angle} = 180° - \text{inner\_angle} \tag{3.2}$$

Where the reflector length is the length of the mirrors used, and the target width is the width of the surface of the PV module.

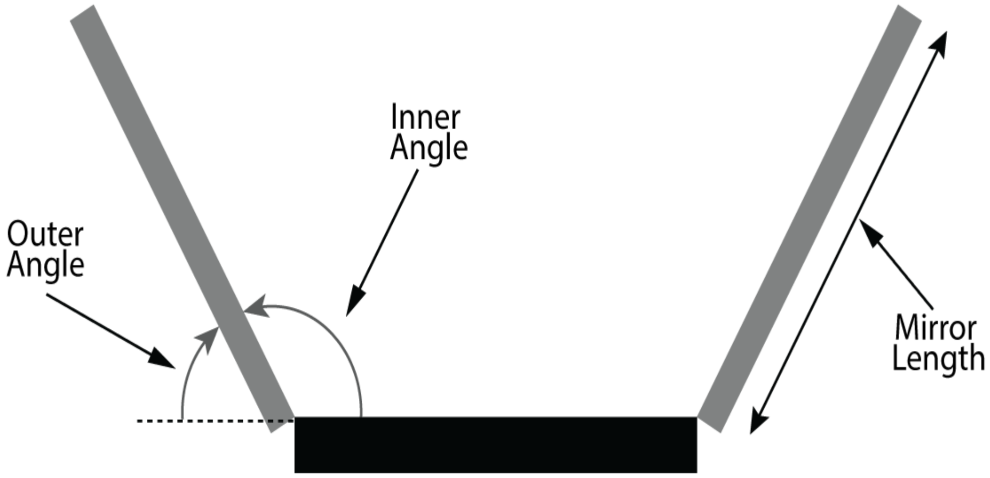

Figure 9: Angular positioning of the mirrors

3.3 Performance analysis of the CPV/T

To access the electrical and thermal performance of a PVT system, several models and formulas exits which give a direct calculation of measured values. The overall efficiency of the CPV/T system is the electrical + thermal efficiencies, given by;

$$\eta_o = \eta_e + \eta_{th} \tag{3.3}$$

Where η_o, η_e, η_{th} represent the overall, electrical, and thermal efficiencies, respectively.

3.3.1 Thermal performance of CPV/T collector

The assessment of the thermal efficiency involves the calculations of various temperature values throughout the CPV/T system, taking into account the ambient temperature T_{amb}, temperature of the fluid T_f, T_{cell} is the temperature value of the PV cell and with all these we can calculate the thermal output Q_u in the system. The expressions for calculating these values are as follows;

The temperature of the PV cell could be calculated by[31]:

$$T_{cell} = \frac{(\alpha\tau)_{eff}G + U_T T_{amb} + U_T T_g}{U_T + U_t} \tag{3.4}$$

Where U_T and U_t represents the total heat transfer coefficient flowing from the PV cell to the flowing water and the ambient, respectively. $(\alpha\tau)_{eff}$ represents the product of the absorptivity and transmittivity. $T_g$is the temperature of the glass calculated as;

$$T_g = \frac{h_{p1}(\alpha\tau)_{eff}G + U_T T_{amb} + h_f T_f}{U_{tT} + h_f} \tag{3.5}$$

Where h_{p1} is the correction factor due to the presence of the glass, EVA and the PV cell material. h_f is the heat transfer coefficient of the fluid, U_{Tt} is the overall heat transfer coefficient, T_f is the temperature of the fluid given by;

$$T_f = \left(T_{amb} + \frac{(\alpha\tau)_{eff}Gh_{p1}}{U_L}\right)\left(1 - \left(\frac{1-\exp\left(\frac{-\acute{F}WU_LL}{Cp\dot{m}}\right)}{\frac{WU_LL}{Cp\dot{m}}}\right)\right) + T_{f,in}\left(\frac{1-\exp(-\acute{F}WU_LL)}{\frac{WU_LL}{Cp\dot{m}}}\right) \tag{3.6}$$

Where U_L is the heat loss coefficient from the PV/T to the surrounding, $\acute{F}$ is the effieciency of the flat plate collector, W and L are the width and length of the PV/T, respectively. And C_p is the specific heat of the flowing fluid.

The thermal output of the system is given by;

$$Q_u = \dot{m}C_p(T_{out} - T_{in}) \tag{3.7}$$

Where T_{out} and T_{in} represnts the waters outlet and inlet temperatures respectively, $\dot{m}$ is the mass flow rate of the cooling water and C_p is the specific heat of water, see Appendix A for a list of the properties of water at several temperatures.

The thermal efficiency of the CPV/T collector is given by;

$$\eta_{th} = \frac{Q_u}{AG} \tag{3.8}$$

Where A is the area of the collector.

3.3.2 The electrical performance of the CPV/T collector

For the electrical performance, we need certain parameters such as the voltage V, current I, and power P.

$$P = IV \tag{3.9}$$

The electrical efficiency is given by;

$$\eta_e = \frac{P}{GA} \tag{3.10}$$

If we want to evaluate the electrical efficiency based on the temperature of the PV cell, the following expression is preferred;

$$\eta_e = \eta_{rc}[1 - \beta_{PV}(T_{PV} - T_{rc})] \tag{3.11}$$

Where η_{rc} is the initial electrical efficiency measure at STC, β_{PV} is the temperature coefficient of the cell.

Chapter 4

4 EXPERIMENTAL SETUP AND PROCEDURE

In this chapter, the experimental setup and test procedures are presented. Two separate systems were setup, the reference module which is a plain PV panel with no modifications and the CPV/T system, both were mounted on the roof of the Mechanical Engineering Department of the Eastern Mediterranean University.

The Figure 10 shows the setup of the system on the roof. Sun tracking was done in both cases and the cooling water was in an open-loop through the CPV/T collector. The water was maintained at 0.006kg/s as the optimal flow rate for maximum thermal output. This was empirically determined as several tests were done to obtain the proper flow rate.

The temperatures were taken using a Vichy DM6801A Digital thermometer as shown in the Figure 11 below. K-type thermocouples were used in the measurements. All devices used in this study were calibrated and accuracies ascertained and shown in Table 2 below.

Figure 10: Picture of the CPV/T setup

Table 2: Accuracy of the instruments used

Instrument	Accuracy
Digital Thermometer	± 0.5 ℃
Pyranometer	$8\mu V/(W/m^2)$
VICHY VC9805A+ Multimeter	Current: 2%; Voltage: 0.25%

The voltage and current were measured with a VICHY VC9805A+ Multimeter as shown in Figure 12 below.

An Eppley Pyranometer was used to measure the solar irradiance on the PV panel as shown in Figure 13 below. Which is connected to the multimeter and calculated thus;

$$G = \frac{V*1000}{10.5} \tag{4.1}$$

Where V is the measured voltage from the multimeter given in mV.

Figure 11: Vichy DM6801A Digital thermometer

Figure 12: VICHY VC9805A+ Multimeter

Figure 13: Eppley Pyranometer

A test was also done using a diffusing glass to diffuse the reflections on the PV panel. The glass was placed on the mirrors and adjusted for accurate angle. This was done to ensure even distribution of the solar rays on the PV surface. The diffusing glass is shown in the Figure 14 below and a schematic diagram of the diffraction is shown in Figure 15.

Figure 14: Diffusing glass

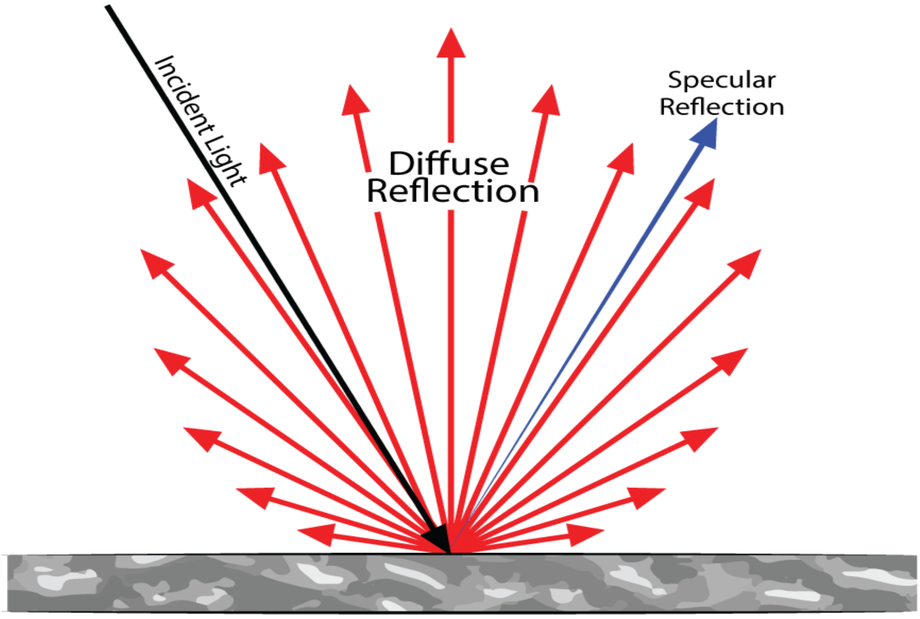

Figure 15: A schematic diagram of solar diffusion

Chapter 5

5 RESULTS AND DISCUSSIONS

A series of test were conducted in June 2015 with clear and sunny weather between the hours of 9:00 to 17:00 h.

5.1 Experimental results

The PV panel, which has a power rating of 15 W at STC had its maximum electrical power output of 20.819 W at a solar irradiance of G= 895.2381 W/m² under the weather conditions of Northern Cyprus. The system was manually tracked, and had a maximum power output of 20.819 W with an average efficiency of $\boldsymbol{\eta_e}$**= 15.4 %** see Table 3.

Table 3: Electrical performance of the PV panel

Time	**Voltage [V]**	**Current [A]**	**Power [W]**	**Surface Temp [℃]**
9:00	19.1	1.09	20.82	35
10:00	19.5	0.96	18.72	38
11:00	20.1	0.97	19.50	43
12:00	20.1	0.99	19.90	48
13:00	20	0.99	19.80	50
14:00	19.7	1.02	20.09	51
15:00	19.3	0.98	18.91	48
16:00	18.6	0.9	16.74	44
17:00	18	0.88	15.84	38

The performance of the CPV/T collector was examined under 5 different conditions and their efficiencies compared to that of the reference module.

5.1.1 CPV/T collector with uncontrolled inlet temperature

Table 4: CPV/T collector with uncontrolled inlet temperature

Time	Voltage [V]	Current [A]	Power [W]	Tin [°C]	Tout [°C]	ΔT [°C]
9:00	20.9	1.09	22.78	26	28	2
10:00	21.2	1.29	27.35	28	33	5
11:00	21.4	1.34	28.68	34	39	5
12:00	21.7	1.54	33.42	37	38	1
13:00	20.9	1.33	27.80	38	40	2
14:00	20.6	1.31	26.98	40	42	2
15:00	19.9	1.26	25.07	38	40	2
16:00	19.7	1.01	19.90	35	39	4
17:00	19.2	0.98	18.81	31	35	4

Where Tpanel, Tin, Tout, ΔT represents the temperature of the PV surface, the inlet temperature of the cooling water, the exit temperature of the cooling water, and the difference between the inlet and exit temperatures of the cooling water.

As shown in the Table 4 above, the temperature of the inlet water was uncontrolled, that means that it was open to the ambient temperature. It's max electrical power was **P= 33.418** $\boldsymbol{W_P}$ at G= 1304.762 W/m², the electrical efficiency is $\boldsymbol{\eta_e}$**= 15.01 %.** The thermal efficiency $\boldsymbol{\eta_{th}}$ **=44.243%** and thermal output $\boldsymbol{Q_u}$**= 75.339 W**

5.1.2 CPV/T collector with controlled inlet temperatures

Table 5: CPV/T collector with 22°C inlet temperature

Time	**Voltage [V]**	**Current [A]**	**Power [W]**	**Tin [°C]**	**Tout [°C]**	**ΔT [°C]**
9:00	21	1.2	25.20	22	23	1
10:00	20.7	1.31	27.12	22	25	3
11:00	21.3	1.6	34.08	22	26	4
12:00	21.7	1.9	41.23	22	27	5
13:00	21.6	1.79	38.66	22	27	5
14:00	21.4	1.65	35.31	22	26	4
15:00	21.1	1.38	29.12	22	25	3
16:00	20.8	1.17	24.34	22	24	2
17:00	20.3	0.98	19.89	22	24	2

To properly test the effects of temperature, it was important to maintain a constant inlet temperature. Fixing the inlet temperature constant at 22°C, the CPV/T showed an improved power as shown in the Table 5 above, the main reason for the improvements is the lowered working temperature of the module, as it has been established that high temperatures reduces the efficiency of the PV cell.

From this a series of test were done using inlet temperatures of 18°C, and 14°C as is seen in Tables 6 & 7 to further examine the effect of the PV working temperature on the overall. The maximum power output for the 18℃ inlet temperature was 44 W_P and for that of 14℃ was, 49.06 W_P and this shows a clear proof of the effect of the coolant inlet temperature.

The averages of these test are summarized in Table 8. From these results it can be concluded that the CPV/T has the highest overall efficiency when the temperature was at 14°C, see Figure 17 below.

Table 6: CPV/T With 18°C inlet temperature

Time	**Voltage [V]**	**Current [A]**	**Power [W]**	**Tin [°C]**	**Tout [°C]**	**ΔT [°C]**
9:00	21.1	1.2	25.32	18	20	2
10:00	21.4	1.51	32.31	18	21	3
11:00	21.8	1.87	40.77	18	22	4
12:00	22	2	44.00	18	23	5
13:00	21.6	1.8	38.88	18	23	5
14:00	21.6	1.76	38.01	18	23	5
15:00	21	1.7	35.70	18	22	4
16:00	20.8	1.4	29.12	18	20	2
17:00	20.5	1.12	22.96	18	20	2

Table 7: CPV/T With 14°C inlet temperature

Time	**Voltage [V]**	**Current [A]**	**Power [W]**	**Tin [°C]**	**Tout [°C]**	**ΔT [°C]**
9:00	21.4	1.34	28.68	14	16	2
10:00	21.6	1.91	41.26	14	18	4
11:00	22.1	2.2	48.62	14	18	4
12:00	22.3	2.2	49.06	14	19	5
13:00	22	2.03	44.66	14	19	5
14:00	21.7	2	43.40	14	19	5
15:00	21.4	1.86	39.80	14	18	4
16:00	21	1.4	29.40	14	16	2
17:00	20.5	1.04	21.32	14	16	2

Table 8: Summary of the Average of the CPV/T performance.

Inlet Temp	Power [W]	Q_u [W/m²]	η_{th} [%]	η_e [%]	η_o [%]
14	38.47	92.08	53.35	22.40	75.75
18	34.12	89.29	51.36	19.73	71.09
22	30.55	80.92	46.73	17.73	64.46
Amb	25.64	75.34	44.24	15.01	59.10
Reference	18.93	0	0	15.36	15.36

The Figure 16 below is the a graphical presentation results of the power outputs obtained during this study.

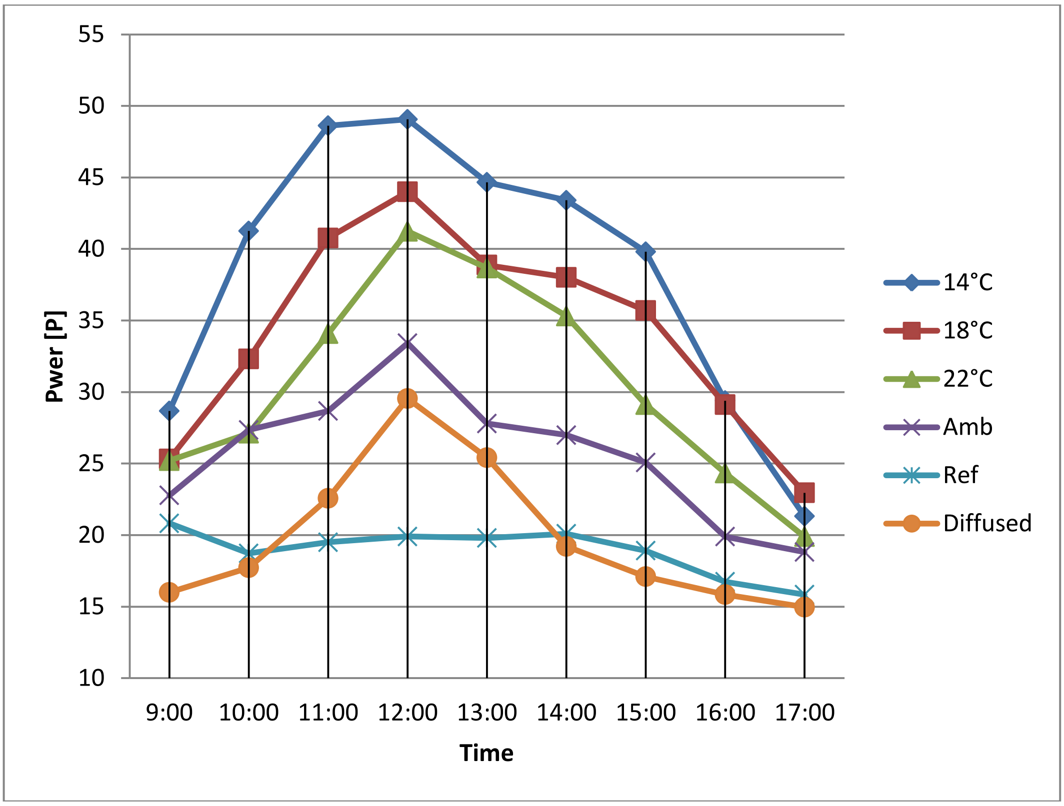

Figure 16: Power versus Time

Finally, a test was also done using a diffusing glass, and the intent of the test was to find out the effect of diffusing the reflected solar irradiation to have a uniform reflection on the surface of the PV panel. This was done using a glass with a relatively smooth texture as shown in Figure 14 above, while using the inlet temperature of the cooling water set to 22°C. The results of the test showed a lower power output when compared to the Undiffused test results under the same climatic conditions,see Figure 16 above, this could be as a result of the thickness and texture of the glass. During its test, the glass did improve the effect of just 1 mirror and lowered the effect of others as the concentration from each mirror changes every hour as the sun moves. The objective of uniform distribution of the radiation was met, but the resulting concentration was poor.. See Table 9 below for the results of the diffused test.

Table 9: Diffused test results

Time	**Voltage [P]**	**Current [A]**	**Power [W]**
9:00	17.2	0.93	15.99
10:00	17.9	0.99	17.72
11:00	19.8	1.14	22.57
12:00	20.1	1.47	29.55
13:00	19.7	1.29	25.41
14:00	19.4	0.99	19.20
15:00	18	0.95	17.10
16:00	17.8	0.89	15.84
17:00	17.6	0.85	14.96

From the summary in Table 9 above, it is clear that the energy loss in the CPV/T is much less than that of the reference module and that is shown in the Charts and graphs below

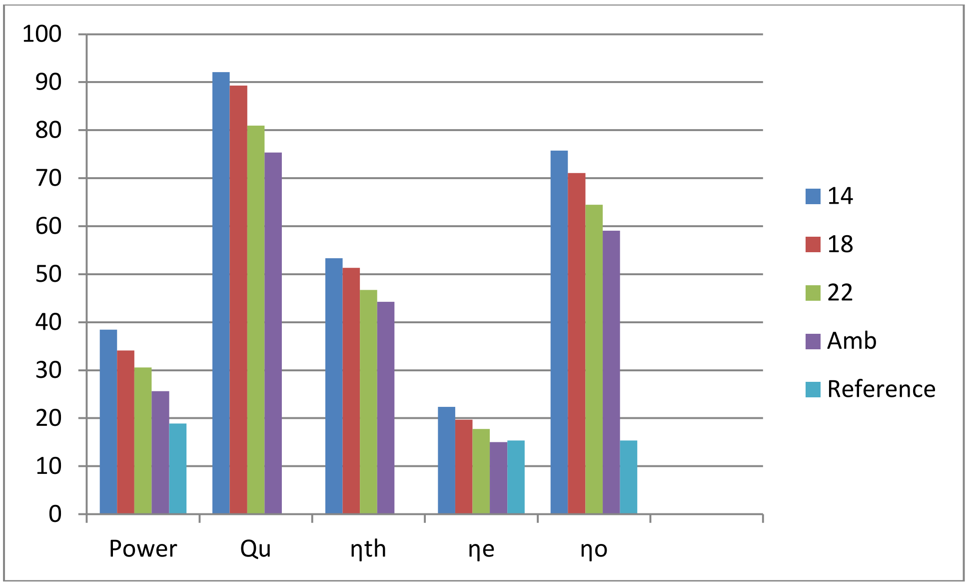

Figure 17: Comparison of the CPV/T and PV Performance

Where Qu is the thermal output, ηth is the thermal efficiency, ηe is the electrical efficiency, ηo is the overall efficiency.

The chart shows a clear view of the average outcomes of all tests conducted using various inlet temperatures and the reference PV panel with that of the 14°C inlet temperature having the best results.

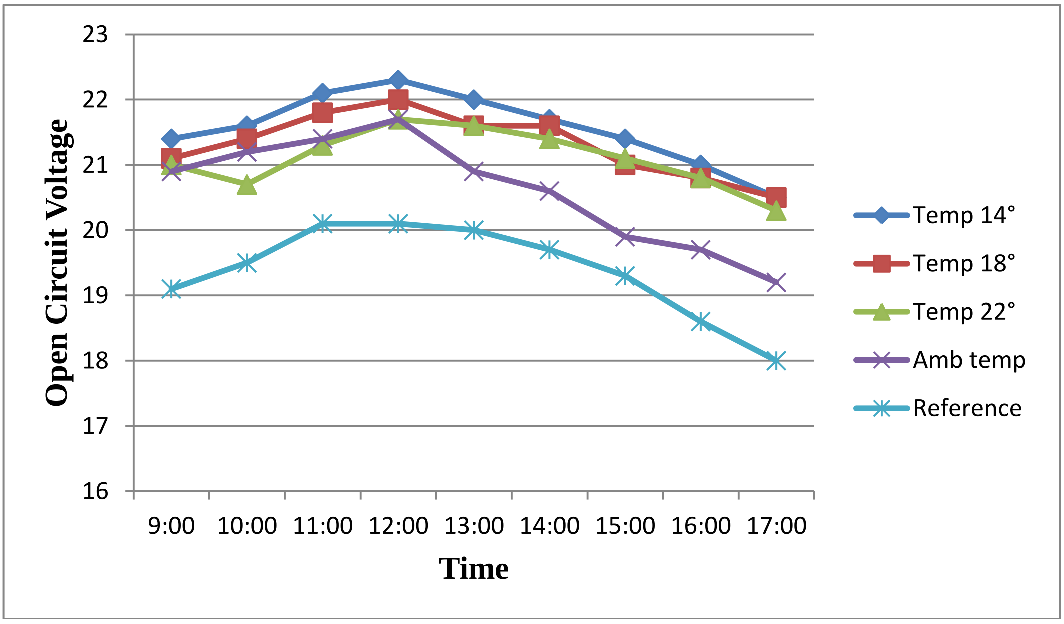

Figure 18: Voltage comparison of the CPV/T and PV systems

The Figure l8 above shows the flow of voltages in Time. The voltage slightly decreases or remains unchanged as temperature increases and that leads to a drop in the power output of the CPV/T collector.

The Figure 19 shows the current variations with respect to Time. The current is directly influenced by the amount of solar radiation focused on the PV cells.

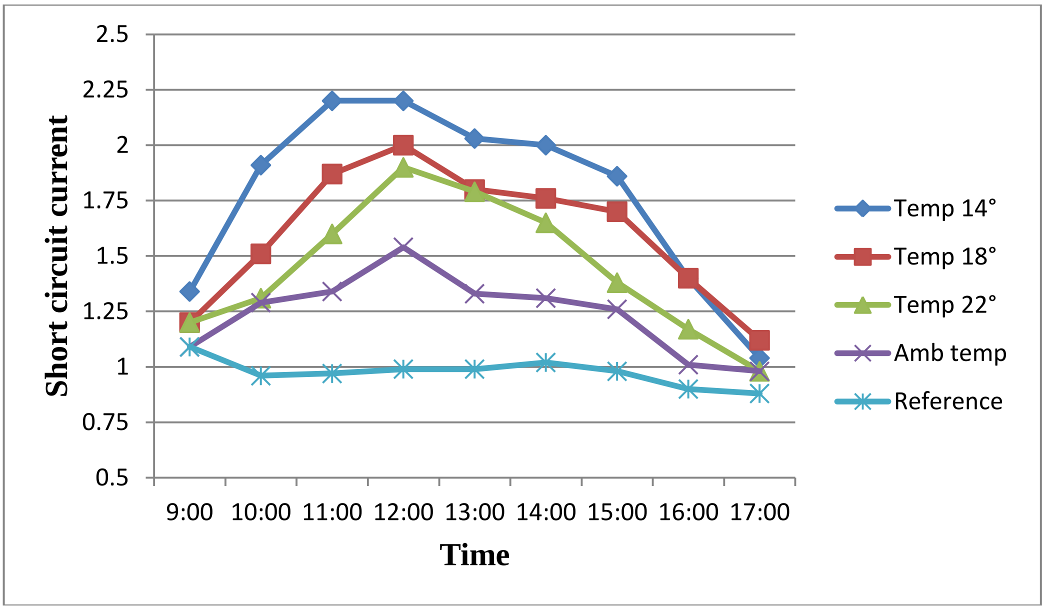

Figure 19: comparison of short circuit current versus Time of the CPV/T and PV systems.

5.2 Error analysis

As in every experiment, there are errors in measurements, and apparatus that the experimenter must take note of and also consider in his analysis and calculations. There are three main types of errors that could occur during an experiment. First, are the outright blunders in the reading of the observations, omissions in recording digits, and also in the apparatus construction. These should be easily spotted by a careful experimenter and eliminated, as they should not be added to the analysis. Second, are the systematic errors or sometimes called bias errors, and could be in four different form:

- Instrumental. This arises from poorly calibrated equipments and do alter the measured readings.
- Observational. Such as parallax when reading a meter scale.
- Environmental. These are imposed by the environmental factors surrounding the experiment.
- Theoretical. Comes from simplification of model system or the approximation done in the equations for the sake of simplicity

Third, is called the *random error,* this is as a result of various fluctuations which in most cases is difficult to control and follows a certain statistical distribution[32]. In talking about experimental errors, we are interested in finding the uncertainty in the final result due to the uncertainties in the primary measurements. This may be done by taking into account the uncertainties in each variable in the calculations and this will be summed up in the final equation. The result *R* is as a function of the independent variables $x_{1,}x_2, \ldots, x_n$,

$$R = R(x_{1,}x_2, \ldots, x_n) \tag{5.1}$$

Let the uncertainties of the result *R* and the variables be represented by $w_R, w_1, w_2, w_3, \ldots, w_n$

$$w_R = [\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2]^{1/2} \tag{5.2}$$

For product functions, the equations 6.1 and 6.2 above could be rewritten in the form

$$R = x_1^{a_1} x_2^{a_2} \ldots x_n^{a_n} \tag{5.3}$$

$$\frac{w_R}{R} = [\sum(\frac{a_i w_{x_i}}{x_i})^2]^{1/2} \tag{5.4}$$

For the addictive functions, the equations 6.1 and 6.2 above could be rewritten as

$$R = \sum a_i x_i \tag{5.5}$$

$$w_R = \left[\sum (a_i w_{x_i})^2\right]^{1/2} \tag{5.6}$$

Where $a_i = \frac{\partial R}{\partial x_i}$

For this study the uncertainty of the maximum power and thermal outputs and efficiencies, would be calculated.

The electrical power output of the system was calculated as P=IV, taking into the accuracy readings of the instruments used from Table 2 above, with current as ±2% and voltage as ±0.25%. and the thermal output of the system was calculated as $Q_u = \dot{m} C_p (T_{out} - T_{in})$, with mass flow rate ±10%, Temperature ±0.5°C, and solar radiation G ±8$\mu V/(W/m^2)$.

The tables 10 and 11 shows the summary of the maximum electrical and thermal outputs and efficiencies with their correlated uncertainties.

Table 10: Electrical performance

Test	**Power [W]**	**Efficiency [%]**
Temp 14°	49.06 ± 1.1	27.15 ± 0.77
Temp 18°	44 ± 0.99	24.35 ± 0.69
Temp 22°	41.23 ±0.93	22.82 ± 0.65
Amb temp	33.42 ±0.75	18.49 ± 0.53
Reference	21.91 ± 0.49	12.13 ± 0.34

Table 11: Thermal performance

Test	Q_U **[W]**	**Efficiency [%]**
Temp 14°	125 ± 2.5	69.2 ± 1.8
Temp 18°	125 ± 2.5	69.2 ± 1.8
Temp 22°	125 ± 2.5	69.2 ± 1.8
Amb temp	125 ± 2.5	69.2 ± 1.8
Reference	0	0

Chapter 6

6 ECONOMIC ANALYSIS

In this chapter, the economic analysis of a PV and CPV/T system will be discussed, considering a system of 5 kWp capacity residential systems.

The cost analysis of a PV system, includes the PV panel and BOS cost. The BOS cost includes several components such as, the battery, electrical systems, and similar components. An estimated minimum BOS cost for an average residential system is about USD 1.6/W [33], hence the BOS cost of a 5 kWp system;

USD 1.6/W x 5000 Wp = USD 8000

This cost is similar for both the plain PV modules and the CPV/T collector as the BOS components would be similar.

Using a 15 Wp PV module, the total cost to setup a residential PV module to generate 5 kWp of electrical power would be:

$$\text{Total number of modules required is} = \frac{Required\ capacity}{PV\ module\ capacity} \qquad (6.1)$$

Using the average electrical output of from Table 3 above, which is P= 18.92 W, the number of required modules for 5 kW is about 264.

An estimate of about USD 1.33/W, for the 15 W PV module the cost would per module would be about USD 20, therefore 264 modules would cost = USD 5280

The total cost to set up the residential 5 kW PV systems = Cost of PV modules + Cost of BOS

Which amounts to a total of USD 13280

The CPV/T system consists of a PV module, metal pipes, plane mirrors, and plain transparent glass. The estimated cost of the CPV/T system is about USD 35.

Using the CPV/T with inlet temp of 14°C, the average power output is P = 38.47 W, which gives a total of 130 CPV/T collectors required for the 5 kW system.

The total cost for the 5 kW CPV/T system = Cost of 130 CPV/T collectors + cost of BOS, which amounts to USD 12550.

Estimated annual thermal energy output = daily output x 365 days

= 0.126 kWh x 130 collectors x 365 days

= 5978.7 kWh

The annual savings on thermal energy = annual thermal output x energy price (USD 0.22/ kWh), which is = USD 1315.31

The annual savings on electrical power is = system capacity x energy price

= 5000 W x USD 0.22/kWh = USD 1100

The Life cycle cost analysis of the 5 kW PV and CPV/T system is done taking into account that the:

- Total annual savings for the PV system is = USD 1100
- Total annual savings for the CPV/T system = thermal + electrical savings = USD 2415.31

There are a number of indicators to be considered in the Life Cycle Cost analysis:

- The Net Present Value (NPV) signifies the sum of the present values of the cash flows within a period of time, values > 0 shows that the project is economically feasible.
- Savings-to-Investment (SIR) this gives the ratio of the savings to investment, where value of 1 shows that the investment is completely regained, values greater than 1 shows that the savings will be more than and values less than 1 shows that the investment would be greater than savings of the period of time analyzed
- Internal rate of return (IRR) is the discount rate where the net present value of the investment becomes zero, it is the discounted rate which makes the present value of the future cash flows of an investment equal to the initial investment.

A 20 year lifetime was considered, with a 4% Discount Rate, and a residual value of USD 5000 and the results are shown in the Table 12 & 13 below

Table 12: LCC Analysis for the CPV/T system

Results	**OUTPUTS**
Net Present Value (NPV)	**$21 498**
Savings-to-Investment Ratio	**2.9**
Internal Rate of Return (IRR)	**18%**
Simple Payback (years)	**5.2**

Table 13: LCC Analysis for the PV system

Results	**OUTPUTS**
Net Present Value (NPV)	**$3 200**
Savings-to-Investment Ratio	**1.3**
Internal Rate of Return (IRR)	**6%**
Simple Payback (years)	**12.1**

From the given results of the Life Cycle Cost Analysis above both the PV and CPV/T systems are feasible projects because their NPV > 0 and the SIR > 1. But the CPV/T has higher values in terms of the SIR, IRR, and Simple Payback, which makes it an economically better choice of both systems.

Chapter 7

7 CONCLUSION

This project examined the performance of a concentrated photovoltaic/thermal collector (CPV/T). Experiments were done using water as the cooling fluid, with its inlet temperatures varied for optimal inlet temperature of the cooling water. The performance of the hybrid CPV/T system was compared to that of a control PV module tested under the same climatic conditions of Turkish Republic of Northern Cyprus with the month of June 2015.

The experimental results and analysis showed that the CPV/T has a better performance and efficiency than the PV module, and these performances are subjective to the working temperature of the system. It is observed that as the temperature rises, the electrical output of the PV module decreases, but in the CPV/T, the cooling fluid removes the excess heat, thereby increasing the electrical performance and at the same time delivering useful thermal output, this combined output increases the overall performance of the CPV/T system to 75.74% compared to that of the PV module which was 15.36%.

It was also observed that of the 4 cooling water inlet temperature conditions, the best was the 14°C inlet water, which has an overall performance of 75.74%, and a peak electrical power output of 49.06 Wp which is about 3.3 times the rated power of the

PV module. The maximum thermal energy output was 125 Wh for the 14°C inlet temp CPV/T system.

It can be clearly deducted from this study that a decrease in the working temperature of the CPV/T collector would yield an improved electrical and thermal efficiency.

The economic analysis also shows that the CPV/T system has a better chance for success as the combined output improves the economic outlook of the system and makes it a more feasible system than the PV system.

7.1 Future Work

It will be worthwhile to investigate the influence of using a diffusing glass to enable uniform reflection on the PV surface by varing the thickness of the diffusing glass and it’s texture.

Further study could be done by investigating the effect of the size of the mirrors used and the sun tracking efficiency on the performance of the system..

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APPENDIX

Appendix A: Physical Properties Of Water

Temperature **- *t* -**	**Absolute pressure** **- *p* -**	**Density** **- *ρ* -**	**Specific volume** **- *v* -**	**Specific Heat** **- c_p -**	**Specific entropy** **- *e* -**
(^{o}C)	*(kN/m^2)*	*(kg/m^3)*	*10^{-3} (m^3/kg)*	*(kJ/(kg K))*	*(kJ/(kg K))*
0 (Ice)		916.8			
0.01	0.6	999.8	1.00	4.210	0
4 (maximum density)	0.9	1000.0			
5	0.9	1000.0	1.00	4.204	0.075
10	1.2	999.8	1.00	4.193	0.150
15	1.7	999.2	1.00	4.1855$^{1)}$	0.223
20	2.3	998.3	1.00	4.183	0.296
25	3.2	997.1	1.00	4.181	0.367
30	4.3	995.7	1.00	4.179	0.438
35	5.6	994.1	1.01	4.178	0.505
40	7.7	992.3	1.01	4.179	0.581
45	9.6	990.2	1.01	4.181	0.637
50	12.5	988	1.01	4.182	0.707
55	15.7	986	1.01	4.183	0.767
60	20.0	983	1.02	4.185	0.832
65	25.0	980	1.02	4.188	0.893
70	31.3	978	1.02	4.191	0.966
75	38.6	975	1.03	4.194	1.016
80	47.5	972	1.03	4.198	1.076
85	57.8	968	1.03	4.203	1.134
90	70.0	965	1.04	4.208	1.192
95	84.5	962	1.04	4.213	1.250
100	101.33	958	1.04	4.219	1.307