Concentrated Photovoltaic (PV) Cogeneration Systems

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ABSTRACT

Solar photovoltaic (PV) technology systems utilize solar energy to generate electricity. The increment in PV cell's operating temperature causes a significant reduction in the electrical efficiency. In this thesis, a water cooling system was combined with a PV module to construct a type of collectors known as hybrid photovoltaic/thermal (PV/T) collector. PV/T collector operates as a cogeneration system by converting solar energy into electrical energy and thermal energy simultaneously. A concentrating photovoltaic/thermal (CPV/T) collector was then formed by concentrating sunlight onto the collector surface using a set of ordinary flat mirrors to generate more electricity and thermal output at minimal costs. Performance of the CPV/T collector was investigated experimentally and compared with a PV module used as reference. The reference PV module was an ordinary i.e. it was neither concentrated nor cooled. The experimental investigation was conducted in January under climatic conditions of Northern Cyprus. By using two mirrors, the CPV/T collector produced a maximum electrical power output of 32.55 W which is 2.17 times the 15 W rated power of the PV module under standard test conditions (STC) and maximum thermal energy output of 126.23 Wh. When three mirrors were used, the maximum electrical power output was found to be 49.74 W which is 3.3 times the PV rated power and maximum thermal energy output of 189.35 Wh.

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

ÖZ

Güneş fotovoltaik (FV) teknolojisi sistemleri, güneş enerjisini elektrik enerjisine çeviren sistemlerdir. FV hücresindeki çalışma sıcaklığının artışı, elektrik verimliliğinde önemli azalmaya neden olur. Bu çalışmada, bir su soğutmalı sistem ile FV modül kombine edilerek hibrit fotovoltaik/termal (FV/T) olarak bilinen kolektör oluşturuldu. Kojenerason sistemi olarak çalışan FV/T kolektörü güneş enerjisini hem elektrik hem termal enerjiye dönüştürmektedir. Elektrik ve termal enerji üretimini minimum maliyetle artırmak için bir dizi düz ayna kullanılarak kolektör yüzeyine güneş ışınlarını konsantre eden konsantre fotovoltaik/termal (KFV/T) kolektör oluşturuldu. KFV/T kolektörün performansı deneysel olarak incelendi ve referans olarak kullanılan, bir FV modülünün performansı ile karşılaştırıldı. Referans olarak kullanılan FV modüle güneş ışığı konsantresi veya soğutma uygulanmadı. Deneysel inceleme Kuzey Kıbrıs iklim koşullarında Ocak ayı içerisinde gerçekleştirildi. İki ayna kullanılarak oluşurulan KFV/T kolektöründen elde edilen 32.55 W maksimum güç, referans olarak kullanılan ve standard test koşulunda 15W nominal gücü olan modülden 2.17 kat fazladır ve elde edilen maksimum termal enerji 126.23 W saat'tır. Üç ayna kullanıldığı zaman KFV/T kolektöründen elde edilen 49.74 W maksimum güç, referans FV'nin nominal gücünün 3.3 katıdır, ve elde edilen maksimum termal enerji 189.35 W saat'tır.

Keywords: Fotovoltaik, KFV/T kolektör, Elektrik enerjisi, Termal enerji.

Dedicated to

My Father & My Family

ACKNOWLEDGMENT

In the name of Allah, the Most Gracious, the Most Merciful

{He (Allah) it is who made the sun a shining brightness and the moon as a light and ordained for it mansions that you might know the computation of the years and the reckoning. Allah did not create this but in truth. He makes the signs manifest for people who have knowledge.} (Qur'an 10:5).

All the praises and thanks be to Allah, the Lord of the worlds for all the graces and blessings we enjoy.

This thesis would not have been possible without the generous support of my two supervisors, Prof. Dr. Fuat Egelioğlu and Assoc. Prof. Dr. Mustafa Ilkan. They have given me solid guidance and encouragement on every single step to ensure this project succeeds. I was so fortunate to work with them, which allowed me to discover and learn tons of new knowledge under their supervision.

Thanks to my family who has always supported me since the first day and cheers me up exactly when I needed it. Not to forget my colleagues and to all who have been involved directly or indirectly in finishing this project, I wish all of you thanks and good luck.

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LIST OF SYMBOLS

J	Joule
W	Watt
A	Area (m^2)
G	Solar irradiance(W/m^2)
T	Temperature (ºC)
T_{out}	Fluid outlet temperature (ºC)
T_{in}	Fluid inlet temperature (ºC)
T_{amb}	Ambient temperature (ºC)
T_{cell}	PV cell temperature (ºC)
T_{bs}	Temperature of back surface of tedlar (ºC)
eV	Electron volt
K	Boltzmann's gas constant (J/K)
$\dot{m}$	Mass flow rate (kg/s)
V	Voltage (V)
V_{OC}	Open circuit voltage (V)
I_{SC}	Short circuit current (A)
P	Power (W)
Q_u	Useful thermal energy (W)
C_p	Fluid specific heat capacity (J/kg.ºC)
η_{max}	Maximum efficiency
η_{th}	Collector's thermal efficiency
ΔR	Radial spacing of mirrors (m)
ΔA	Azimuthal spacing of mirrors (m)

θ_L	Altitude angle to the receiver from the mirror location of interest (deg)
HM	Height of the mirror (m)
WM	Width of the mirror (m)
r	Tower height (m)
$(\alpha\tau)_{eff}$	The product of effective absorptivity and transmittivity
U_T	Overall heat transfer coefficient from solar cell to flowing water through tedlar ($W/m^2.K$)
U_t	Overall heat transfer coefficient from solar cell to ambient through glass cover ($W/m^2.K$)
U_{tT}	Overall heat transfer coefficient from glass to tedlar through PV cell ($W/m^2.K$)
U_L	Overall thermal loss coefficient ($W/m^2.K$)
U_{tf}	Overall heat transfer coefficient from glass to air through the cell and tedlar ($W/m^2.K$)
h_{p1}	Penalty factor due to the presence of PV cell material, glass and EVA
h_{p2}	Penalty factor due to the presence of interface between tedlar and working fluid
F'	Flat plate collector efficiency
W	Width of CPV/T water collector (m)
L	Dimensions of solar module, duct length, the length of CPV/T water collector, thickness (m)

Chapter 1

INTRODUCTION

In residential homes, solar PV and solar thermal collectors are the most commonly used technologies, where the demand for electricity and hot water has a significant impact on energy bills.

Solar thermal collectors are specific type of heat exchanger systems designed to absorb and convert solar energy into thermal energy. The thermal energy is transferred to a fluid usually water or air and utilized in various applications such as domestic hot water (DHW) and/or central heating. Solar thermal collectors are able to reduce the annual energy consumption of oil and gas to about 60%. This means every year about 35% of the total energy required for domestic hot water can be saved by the combination of solar thermal collectors with condensing boiler [1].

Solar PV technology is an electronic device that utilizes solar energy by converting it into electricity based on operating principle known as the photovoltaic effect. The capacities of solar photovoltaic systems are ranging from less than 1 watt (W) to gigawatts (GW) when used in either on-grid or off-grid applications. The International Energy Agency (IEA) issued a report stating that, since 2010 more capacity of solar photovoltaics has been added to the world than in the previous four decades. In 2013, the capacities of new systems were installed at a rate of 100 megawatts (MW) per day. In early 2014, the total global capacity exceeded 150 GW.

It is estimated that by 2050, 16% of the world's electricity will be produced by solar photovoltaics [2].

PV cells are sensitive to temperature, as the cells operating temperature increases the electrical efficiency and power output also decreases as shown in Fig. 1. The electrical power output of typical silicon PV modules drops per degree Celsius about 0.4 to 0.5%.

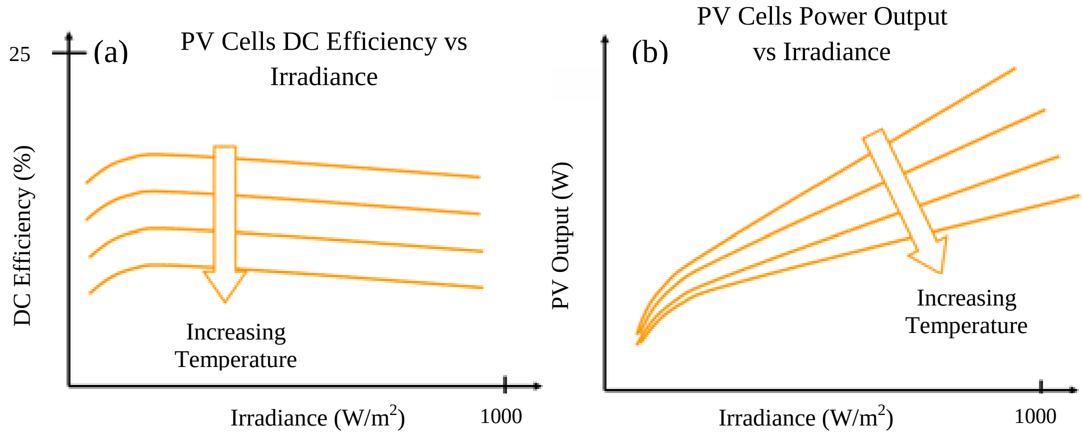

Figure 1. Temperature effect on PV cells: (a) efficiency; (b) power output [3]

A hybrid photovoltaic/thermal (PV/T) collector has been developed to increase the electrical efficiency by removing the accumulated heat through cooling the PV cells by the flow of suitable fluid such as water or air. The hybrid PV/T collector is basically a combination of PV cells and solar thermal components into a single module that enables the use of photovoltaic module as a cogeneration system by converting solar energy into electrical energy and thermal energy simultaneously. Hybrid PV/T collector has a high overall efficiency summing the PV cells electrical efficiency with the collector’s thermal efficiency.

In order to increase the cogeneration effectiveness of a hybrid PV/T collector and particularly to get a higher electrical energy output is to concentrate sunlight onto the PV/T collector surface by using reflectors, mirrors, parabolic trough or paraboloidal dish concentrators. A concentrating photovoltaic/thermal (CPV/T) collector is able to provide up to several times the total electrical power from the same solar cells area and coupled with a thermal output ranging between medium to high temperature. The CPV/T collector uses inexpensive mirrors rather than using expensive solar cells to produce more electricity at low costs.

The main aim of this thesis is to investigate the thermal and electrical performances of a CPV/T collector under climatic conditions of Northern Cyprus. In order to achieve set aim, a low CPV/T collector was constructed by integrating a water cooling system at the backside of a PV module. The collector operates as a cogeneration system by producing electrical energy and thermal energy simultaneously. A set of two and three ordinary flat mirrors were used to achieve the concentration of 2 and 3 suns respectively onto the collector surface in order to increase the thermal and electrical performances. The performances of the collector were studied experimentally and compared with a PV module used as reference.

This work was motivated by several facts:

1. Power generation by burning fossil fuels causes environmental pollution.
2. Installation of PV system is costly.
3. Increment in PV cell temperature causes significant reduction in open circuit voltage that leads to reduction in the electrical efficiency.
4. Limited space on roof is an important factor to influence the idea of combining PV cells and thermal collector into one collector.

5. Installation of PV/T system enables investors to improve the overall efficiency of the system.
6. Low CPV/T collector increases both thermal and power generation of the PV/T collector.

The organization of the thesis is as follows:

Chapter 1 is the introduction. Chapter 2 is a literature review, addressing the previous relevant research works conducted experimentally on hybrid PV/T and CPV/T collectors using water as the cooling fluid. Chapter 3 briefly addresses the design and construction of CPV/T collector along with a discussion of the thermal and electrical performances. Chapter 4 is the experimental setup and procedure followed during the experimental investigation. Chapter 5 presents the results and discussion regarding the performances of CPV/T collector and PV module. Chapter 6 presents an economic analysis of a PV and CPV/T systems. The thesis is concluded in Chapter 7, with some outlook and suggestions of future work.

Chapter 2

LITERATURE REVIEW

Several configurations of hybrid PV/T and CPV/T collectors have been investigated by a large number of research works. The best performance caused by synergistic combination for the cogeneration of electricity and thermal energy by utilizing solar energy is sought.

Concerning the hybrid PV/T collector, Erdil et al. [4] studied experimentally energy generation of hybrid PV/T system at a geographical location in Cyprus. Two PV modules have been used with each having area of about 0.6 m^2. They indicated that 2.8 kWh of thermal energy was produced daily by the hybrid system. An 11.5% electrical energy loss was indicated due to placement of a glass channel for cooling water passage over the hybrid PV/T system.

Chow et al. [5] studied experimentally a PV/T wall system by mounting it on a vertical southwest facade during the late summer in Hong Kong and used for pre-heating the water and power generation. Two circulation mode of water flowing were used; natural and forced. The indicated electrical and thermal efficiencies were 8.65% and 38.9% respectively.

Jiang et al. [6] studied experimentally the performance of a hybrid PV/T system developed in Singapore. The system consists of 6×150 W_p multicrystalline silicon (mc-Si) glazed PV/T collectors. They tested the system for 9 months to evaluate the performance in the tropical region. The system was able to convert solar energy into electrical and thermal energy simultaneously by an average conversion efficiency of 41.05%.

Bahaidarah et al. [7] developed a numerical hybrid PV/T model and also investigated the module experimentally by cooling its backside using water. They found that both the numerical model and experimental measurements are in a good agreement when performed under climatic conditions of Dhahran, Saudi Arabia. Employing active water cooling, the temperature of the module was decreased significantly to about 20% leading to an increase in the PV panel efficiency by 9%.

Fudholi et al. [8] determined the electrical and thermal performances of hybrid PV/T water collectors under 500-800 W/m^2 solar radiation level with mass flow rate ranged from 0.011 to 0.041 kg/s at each level. Three types of absorber were used; web, direct, and spiral flow. The efficiency of spiral flow type PV/T was found to be 65%.

Concerning the CPV/T collector, Kostic et al. [9] designed a low CPV/T collector by mounting flat solar radiation reflectors on the collector to produce more electrical and thermal energy outputs. Both numerical calculations and experimental measurements were performed to determine the optimal position of reflectors on the collector to receive the highest solar irradiance. They found that with reflectors mounted in optimal position on CPV/T collector, the total electrical and thermal energy generated are higher than of those without reflectors.

Ibrahim and Khalil [10] studied experimentally a CPV/T water collector with a tracking system under the climatic conditions of Cairo, Egypt. The system consists of two PV/T panels with the upper one receives 1 sun irradiance and the lower receives 4 suns irradiance from a concentrator made by using four ordinary mirrors. The system was automatically tracking the sun and using water cooling. The power produced was indicated to be 3 times the power produced by the normal PV module, and hot water with average temperature of 53 ºC was obtained.

Chengdong et al. [11] studied the electrical and thermal outputs of low CPV/T collector by designing a concentrator using flat mirrors and Fresnel lens. They found that the thermal and electrical efficiencies were 56% and 10% respectively.

Chapter 3

THE DESIGN OF CPV/T COLLECTOR

3.1 Introduction

Various methods were employed to increase the PV module electrical performance. Many researchers have investigated and suggested the cooling of the PV module by integrating a cooling system either at the front or backside using fluid such as water, air or both. The investigated works were the key role towards the development of hybrid PV/T collectors to convert solar energy into electrical energy and thermal energy within a single collector. The CPV/T collector operates by focusing sunlight onto a receiver (PV/T collector) located at the focal point of a concentrator such as parabolic trough, paraboloidal dish or mirrors. The advantage of using mirrors lead to a CPV/T collector that can provide more electrical and thermal output from the same PV cells surface area. In short, the collector will be able to produce more electrical power and thermal energy with less cost.

3.2 Structure of CPV/T Collector

In this project, two identical PV modules were used having technical specifications shown in Table 1. Each PV module is a 15 W rated power and has efficiency of 10.9%. All technical specifications were measured under Standard Test Conditions (STC) of solar irradiance G=1000 W/m^2, Air Mass - AM=1.5 and cell temperature T=25 ^{o}C. The PV module is shown in Fig. 2.

Table 1. Specifications of each PV module

PV module parameters	Value
Module type	Euro Plus Solar DS-A1-15
Rated maximum 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 module	390×350 mm^2 or 0.1365 m^2
Thickness	25 mm
Weight	1.8 kg

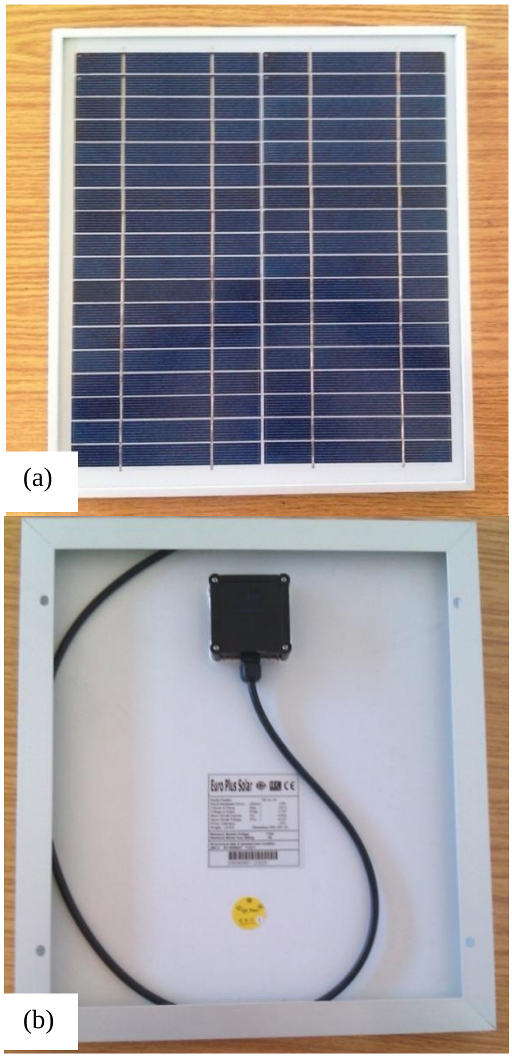

Figure 2. The PV module (a) front; (b) backside with junction box

A cross-sectional view of the PV module along with top view of the backside is shown in Fig. 3. The module comprises PV cells and EVA (Ethylene-vinyl acetate) which are covered by a glass sheet on top and protected by a tedlar film on the backside. All components are assembled within an aluminum frame.

The hybrid PV/T collector composed of a PV module and cooling system added at the backside of the module. To avoid short circuit, a PVC (Polyvinyl Chloride) pipe of 110 mm in length and 140 mm in diameter was used as a protection for junction box from water flowing through the collector. A glass epoxy FR-4 sheet with thickness of 5 mm has been equipped with inlet and outlet port for water flowing, also a round opening which has the same diameter of PVC pipe was made (see Fig. 4).

The hybrid PV/T collector was constructed by attaching the glass epoxy FR-4 material to the backside of the PV module using black silicone adhesive sealant. An insulation layer with thickness of 10 mm was added after the FR-4 sheet to reduce the heat loss from the back of the collector.

The cooling water flows inside the collector through a space of 18 mm between the tedlar and the glass epoxy FR-4, allowing PV module to operate as cogeneration system by capturing the heat from the solar cells and producing warm water at the collector outlet. A cross-sectional view of the PV/T collector along with top view of the backside is shown in Fig. 4.

A 1850 mm long metal pipe was used as a holder, which manufactured in a T-shape as shown in Fig. 5. The system was placed on the roof of the Mechanical Engineering Department. A 290 mm long metal pipe was manufactured in the same shape as shown in Fig. 6. The pipe was attached at the backside of both the PV module and the PV/T collector for suspension on the holder.

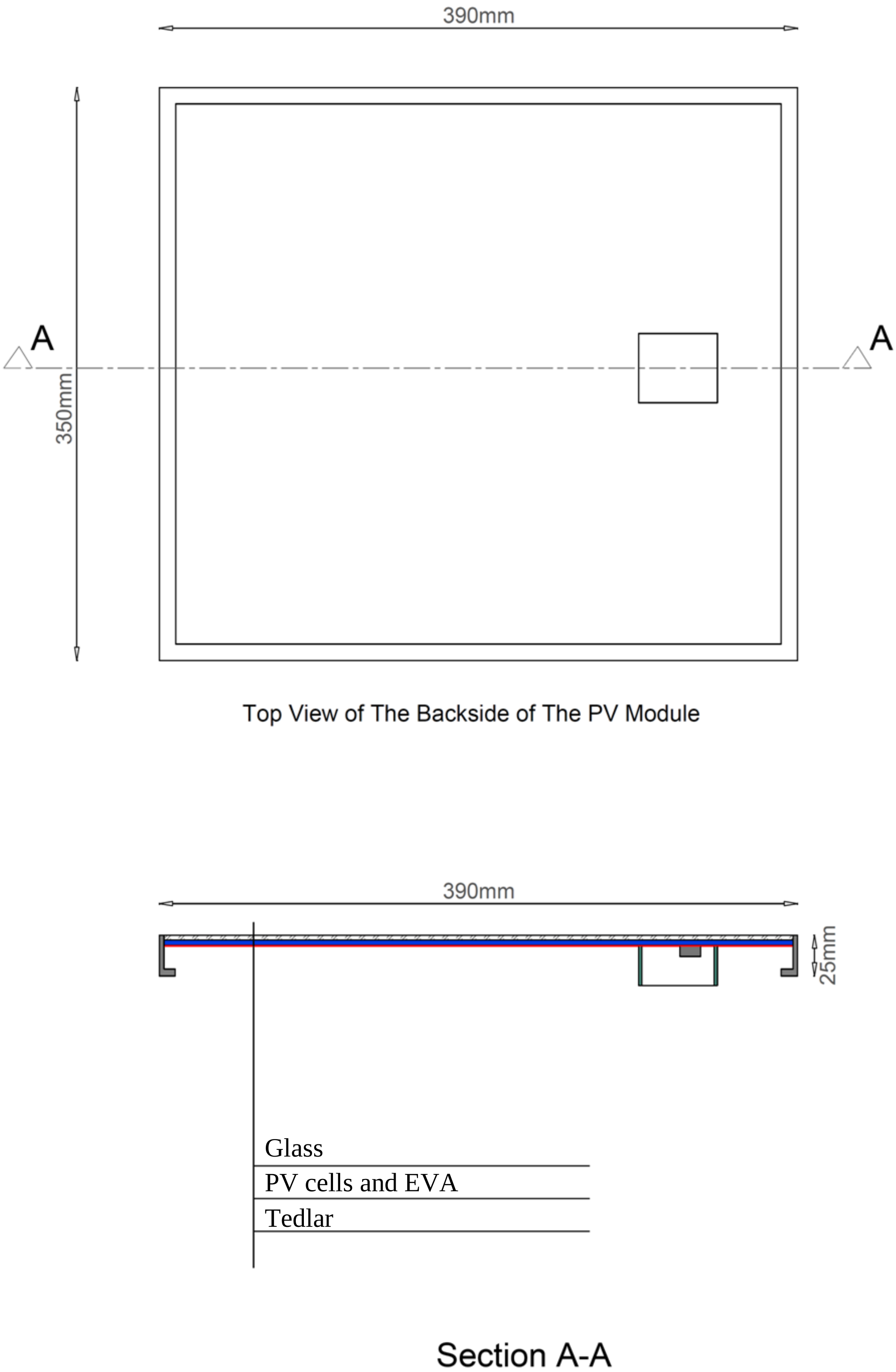

Figure 3. Top and sectional view of the PV module

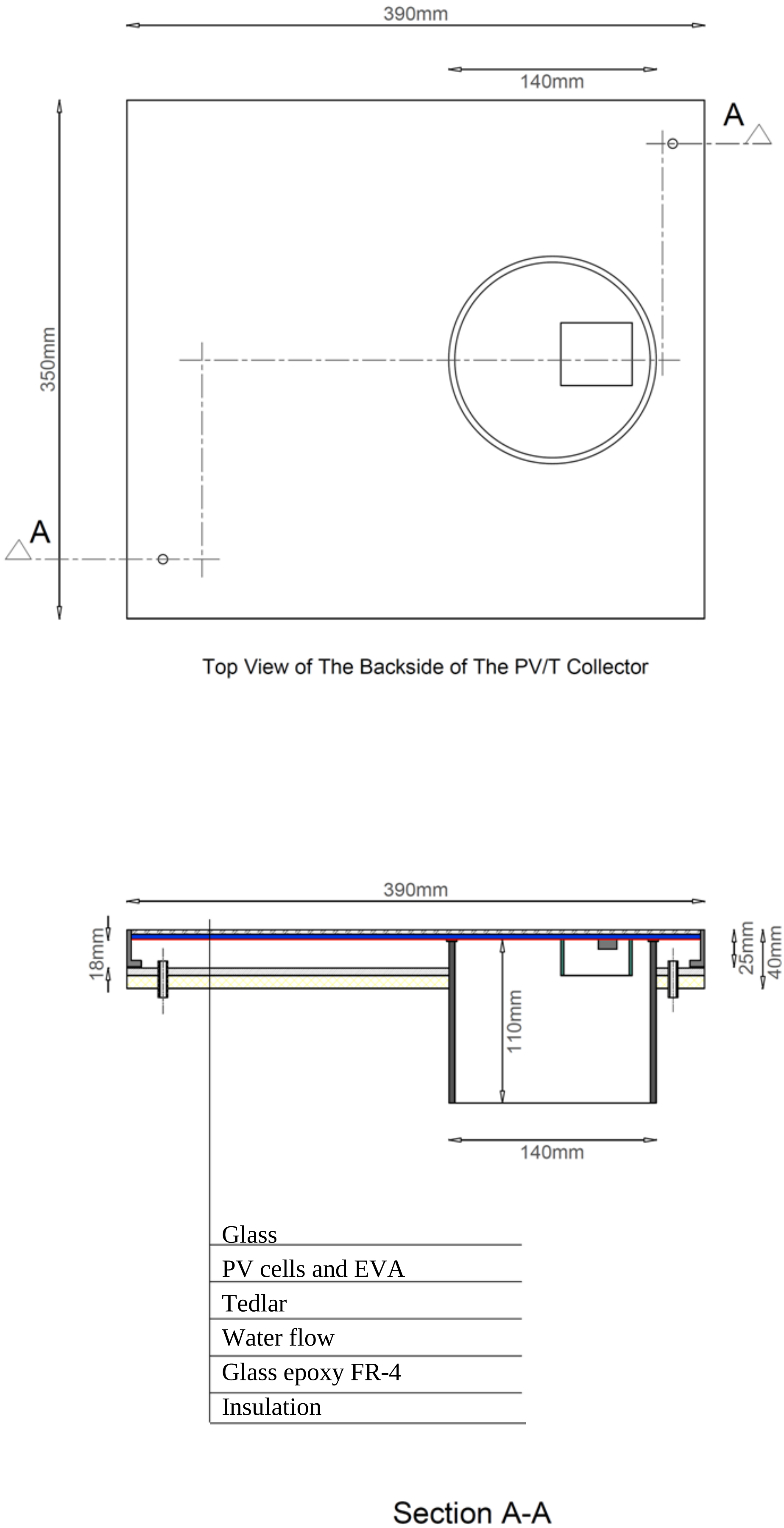

Figure 4. Top and sectional view of the PV/T collector

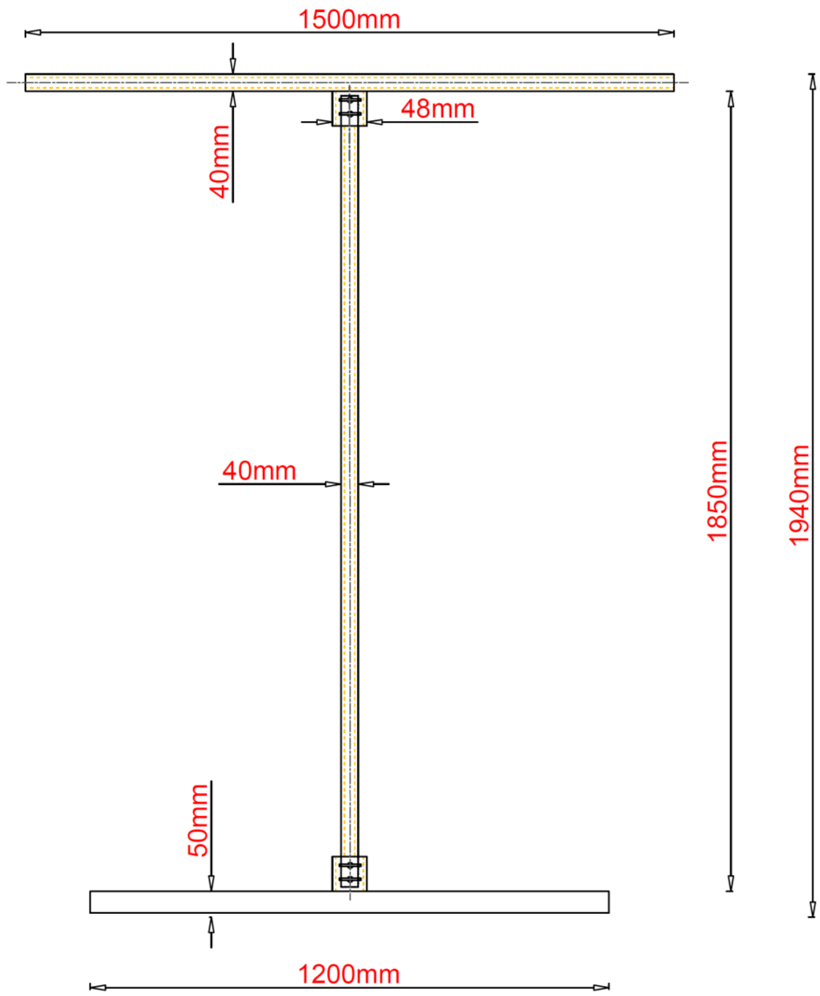

Figure 5. The metal pipe placed on the roof of the department

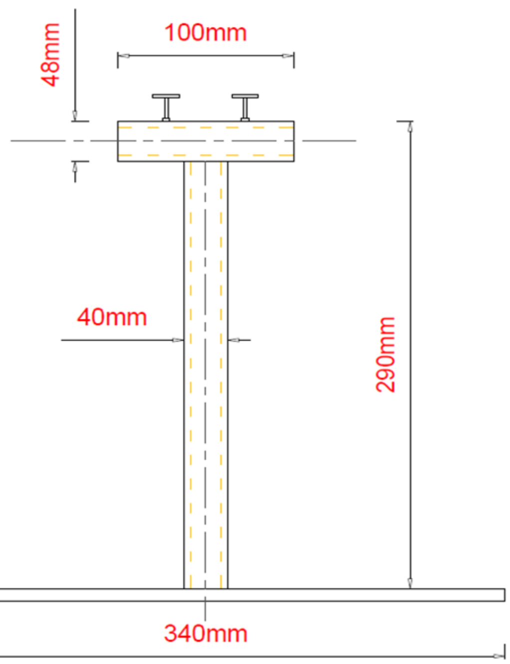

Figure 6. The metal pipe attached on the PV module and the PV/T collector

The CPV/T collector setup was obtained by using a set of ordinary flat mirrors to concentrate sunlight onto the PV/T collector surface. Each mirror has dimensions of 500×500 mm^2. Mirrors have been installed on a movable wooden board that has dimensions of 600×600 mm^2 as shown in Fig 7.

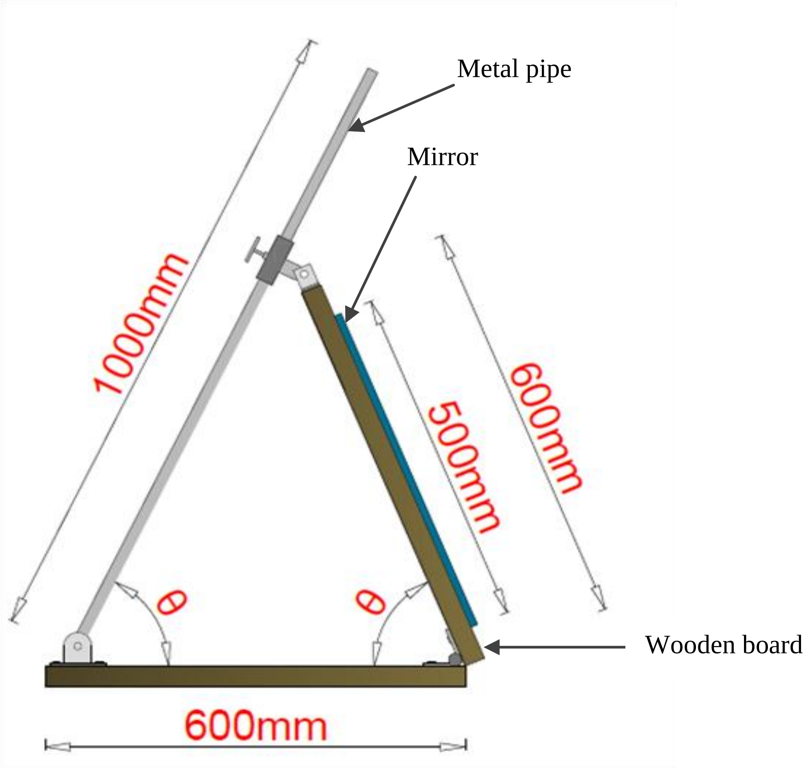

Figure 7. The design of reflectors used in the experiment

For a field layout of mirrors, it is best to arrange them in a radial stagger pattern [12] as shown in Fig. 8.

The mirrors are tightly packed near the holder but sufficiently separated to prevent mechanical interference. For the mirrors located farther from the holder, the spacing increases in order to minimize blocking of the reflected sun beams. If additional mirrors are added by going out along a radius, the spacing becomes too great and new stagger pattern is established [12].

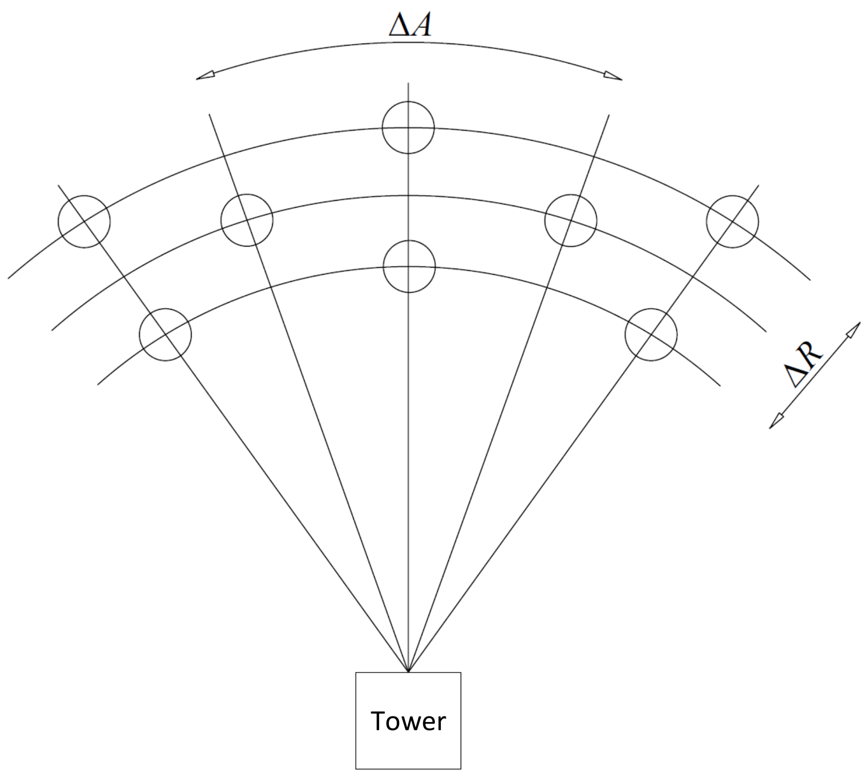

Figure 8. The radial stagger mirror layout pattern

The radial spacing ΔR (m) and the azimuthal spacing ΔA (m) of mirrors are given by [13]:

$$\Delta R = HM\ (1.44 \cot \theta_L - 1.094 + 3.068\ \theta_L - 1.1256\ \theta_L^2) \tag{3.1}$$

and

$$\Delta A = WM\ (1.749 + 0.6396\ \theta_L) + \frac{0.2873}{\theta_L - 0.04902} \tag{3.2}$$

where, HM and WM are the height and width of the mirror respectively.

The angle θ_L (deg) is the altitude angle to the receiver from the mirror location of interest and can be calculated as:

$$\theta_L = tan^{-1}\left(\frac{1}{r}\right) \tag{3.3}$$

where, r is the normalized distance from the tower to the heliostat location measured in “holder height.”

The CPV/T collector provides a better way of utilizing solar energy by obtaining a higher overall efficiency η_o, which is the sum of the PV's electrical efficiency η_e and the collector's thermal efficiency η_{th} and is written as follow [13]:

$$\eta_o = \eta_e + \eta_{th} \tag{3.4}$$

3.3 Thermal Performance of CPV/T Collector

A thermal network diagram which shows thermal resistances through all sections of the collector is presented in Fig. 9. The T_{amb} is the ambient temperature; T_f is the temperature of the flowing fluid; $T_{(section\ name)}$ is the temperature of the section labeled; Q_u is the useful thermal output; R_{rad} is the radiation resistance; R_{conv} is the convection resistance; $R_{(section\ name)}$ is the conduction resistance through the section labeled.

The expression for calculating the PV cell temperature is given as [7]:

$$T_{cell} = \frac{(\alpha\tau)_{eff}\ G + U_T\, T_{amb} + U_T\, T_{bs}}{U_T + U_t} \tag{3.5}$$

where, $(\alpha\tau)_{eff}$ is the product of effective absorptivity and transmittivity; U_T is overall heat transfer coefficient from solar cell to flowing water through tedlar; U_t is overall heat transfer coefficient from solar cell to ambient through glass cover; T_{bs} is temperature of back surface of tedlar and calculated as:

$$T_{bs} = \frac{h_{p1}\,(\alpha\tau)_{eff}\ G + U_T\, T_{amb} + h_f\, T_f}{U_{tT} + h_f} \tag{3.6}$$

where, h_{p1} is penalty factor due to the presence of PV cell material, glass and EVA; h_f is heat transfer coefficient of the flowing fluid; U_{tT} is overall heat transfer coefficient from glass to tedlar through PV cell. The temperature of the flowing fluid T_f is calculated as:

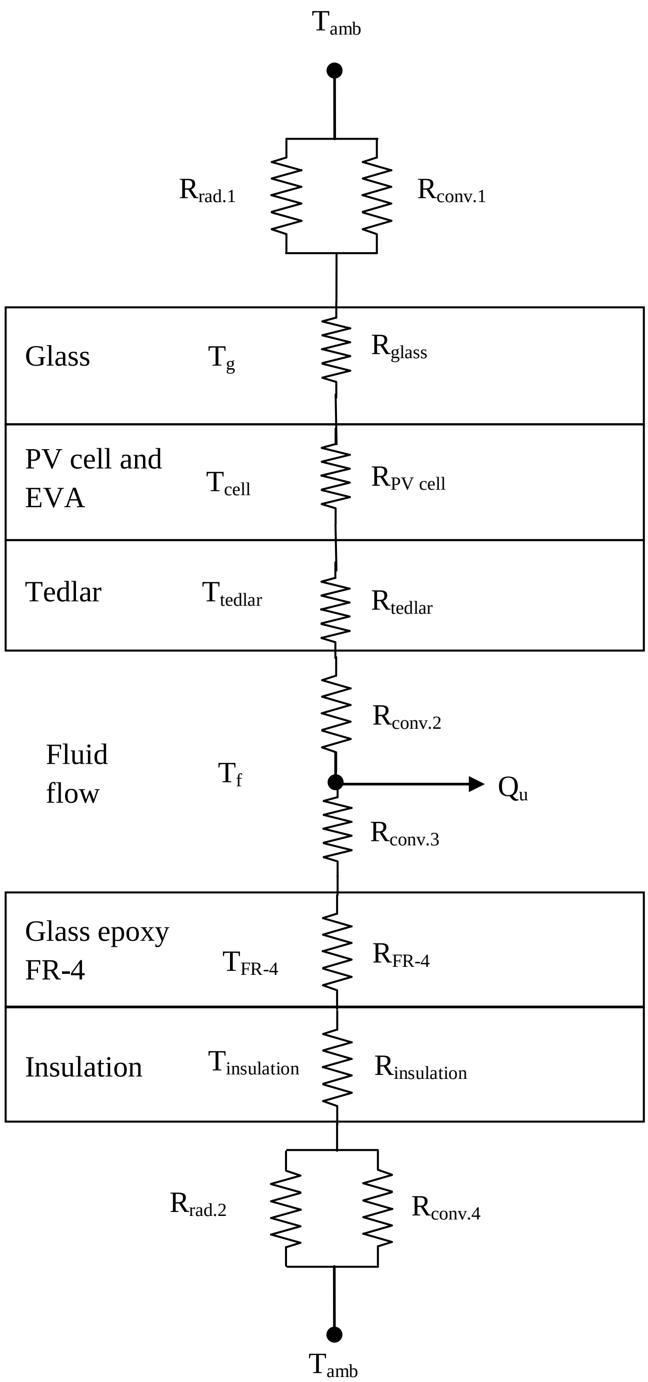

Figure 9. Thermal network of CPV/T collector

$$T_f = \left(T_{amb} + \frac{h_{p1} h_{p2} (\alpha\tau)_{eff} G}{U_L}\right)\left(1 - \left(\frac{1 - \exp\left(\frac{-F' W U_L L}{C_P \dot{m}}\right)}{\frac{W U_L L}{C_P \dot{m}}}\right)\right) + T_{f,in}\left(\frac{1 - \exp\left(-F' W U_L L\right)}{\frac{W U_L L}{C_P \dot{m}}}\right) \quad (3.7)$$

where, h_{p2} is penalty factor due to the presence of interface between tedlar and working fluid; U_L is overall heat loss coefficient from the CPV/T water collector to the environment; F' is the flat plate collector efficiency; W is the width of CPV/T water collector; L is dimensions of solar module, duct length, the length of CPV/T water collector, thickness; C_p is the specific heat of flowing fluid; $\dot{m}$ is the mass flow rate of flowing fluid.

The overall heat transfer coefficient U_{tf} from glass to air through the cell and tedlar is given by:

$$U_{tf} = \frac{1}{\frac{1}{U_{tT}} + \frac{1}{h_f}} \tag{3.8}$$

The useful thermal output Q_u can be calculated from:

$$Q_u = \dot{m}\, C_p\, (T_{out} - T_{in}) \tag{3.9}$$

where, T_{in} and T_{out} are the temperature of the fluid at the collector inlet and outlet respectively.

The CPV/T collector's thermal efficiency η_{th} can be written as:

$$\eta_{th} = \frac{Q_u}{A\, G} \tag{3.10}$$

where, A is the area of the collector.

The difference of absorbed solar radiation, electrical energy produced, and heat loss could be expressed as the useful thermal output [14]:

$$Q_u = A\, [\, G(\tau\alpha) - U_L\, (T_{p,m} - T_{amb}) - Q_e\,] \tag{3.11}$$

where, $T_{p,m}$ represents the mean temperature of absorber plate, which is considered as complex function to calculate or measure due to the different collector designs, working medium properties and incident solar radiation.; Q_e is the PV electrical energy.

3.4 Electrical Performance of CPV/T Collector

The electrical power P produced by the PV cells is the product of the voltage V with the current I and measured in watts (W):

$$P = I\,V \tag{3.12}$$

where the current unit is (A) and voltage is (V).

The CPV/T collector's electrical efficiency η_e can be written as:

$$\eta_e = \frac{P}{A\,G} \tag{3.13}$$

where, A is the area of the PV module.

The dependency of the electrical efficiency on the PV cells working temperature can be written as [15]:

$$\eta_e = \eta_{rc}\,[1 - \beta_{PV}\,(T_{pv} - T_{rc})] \tag{3.14}$$

where, η_{rc} is the initial electrical efficiency at reference temperature; β_{PV} is a temperature coefficient related to the cell efficiency; the PV cell reference temperatures are T_{pv} and T_{rc} respectively.

Equation (3.6) can be used to calculate the generated electrical power as follows:

$$P = \eta_e\,A\,G \tag{3.15}$$

The electrical output is the main priority in most applications, in which the arrangement of heat transfer to the cooling fluid is adjusted to improve the electrical performance.

The CPV/T collector can reach a range of medium to high temperature. The challenge is to remove large quantity of heat from the concentrated area [16], so water is preferably to be used as the cooling fluid since it has a high specific heat capacity compared with air.

Chapter 4

EXPERIMENTAL SETUP AND PROCEDURE

This chapter presents the test setup which consists mainly of a PV module and CPV/T collector. The PV module was used as reference, and is neither concentrated nor cooled. The PV and CPV/T collector were installed on the roof of the Mechanical Engineering Department at the Eastern Mediterranean University, Northern Cyprus. A schematic diagram of the PV module and CPV/T collector setup is shown in Fig. 10.

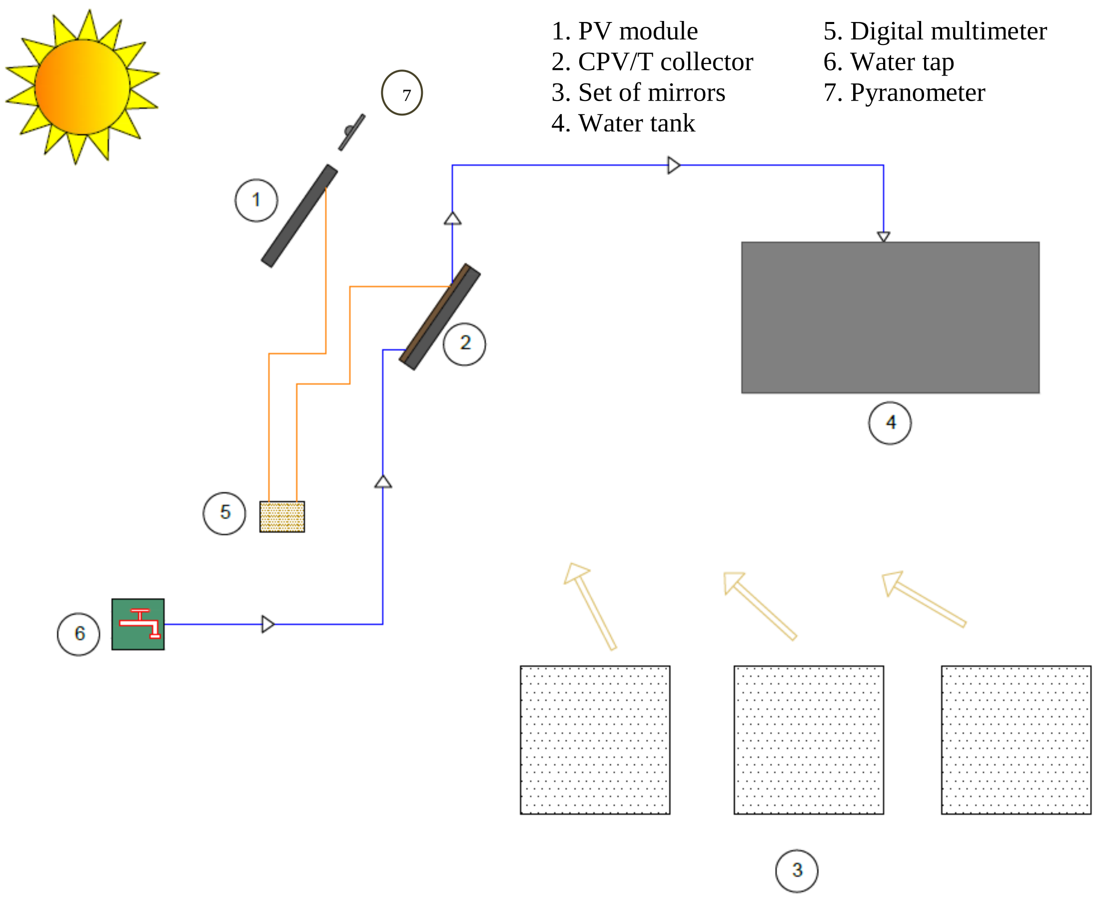

Figure 10. Schematic diagram of the experimental test setup

The CPV/T collector was operated on open-loop cooling mode, in which the cooling water flowed directly from the tap and connected to the collector through PVC (Polyvinyl Chloride) hoses. Due to the small area of the collector, water mass flow rate was kept low i.e., 0.006 kg/s in order to increase the temperature of the exit water.

The water temperatures at the inlet and outlet were measured with K-type thermocouples. Additional thermocouple was used to measure the ambient temperature near to the collector. The thermocouples were connected to digital thermometer with two channels (Vichy DM6801A Digital thermometer) as shown in Fig. 11. A calibration test was done on the thermocouple and the result was in line with the given accuracy from the producer. The accuracy is given in Table 2 along with other instruments used.

Figure 11. Vichy DM6801A Digital thermometer

The solar irradiance on the PV module was measured by using Eppley Radiometer Pyranometer shown in Fig. 12.

Figure 12. Eppley Radiometer Pyranometer

The voltage and current were measured by a digital multimeter (GW multimeter GDM 393A) shown in Fig. 13.

Figure 13. GW multimeter GDM 393A

The accuracy of the instruments used are presented in Table 2.

Table 2. Accuracy of the instruments used

Instrument	Accuracy
Digital thermometer	± 0.5 ^{o}C
Pyranometer	8 μV/(W/m^2)
GW multimeter GDM 393A	Current: 2%; Voltage: 0.25%

The setup of the concentrating PV/T collector was done through adjusting the backside of the collector in a position perpendicular towards the sun; therefore the collector surface is facing the mirrors as shown in Fig. 14. The PV module surface was positioned perpendicularly towards the sun. Both the collector and PV module were manually tracking the sun from east to west.

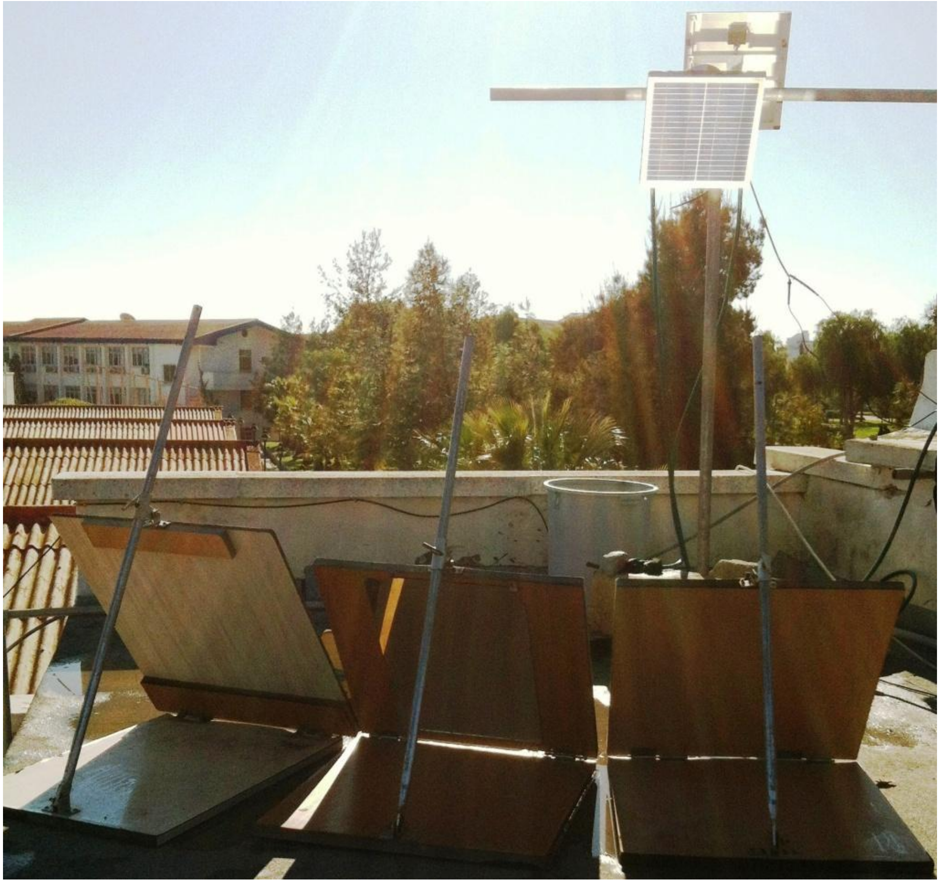

Figure 14. PV module and CPV/T collector setup

The area used by the experimental setup on the roof of Mechanical Engineering Department form a quarter of a circle is shown in Fig. 15. Since one ring of mirrors is used, the radius *r* is equal to the holder height [17]. The area *A* is given by:

$$A = \frac{\pi\, r^2}{4} \tag{4.1}$$

where r = 1.95 m, thus the area is 2.96 m^2.

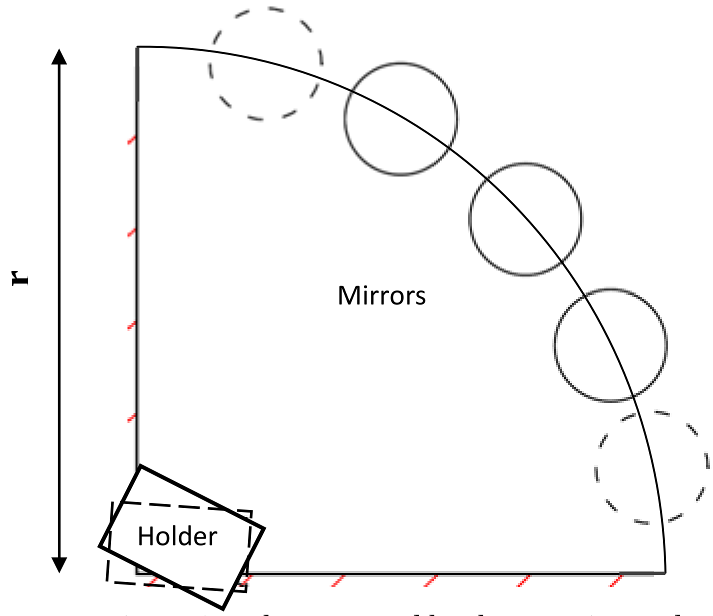

Figure 15. The area used by the experimental setup

Chapter 5

RESULTS AND DISCUSSION

Tests were conducted in January 2015 during the days when the weather was clear and sunny. Data were recorded hourly from 9:30 to 14:30 h.

The PV module is a 15 W rated power measured under Standard Test Conditions (STC). The module was tilted towards the sun rays for maximum solar radiation intercept. The maximum electrical power output produced from the PV module under climatic conditions of Northern Cyprus was found to be 19.83 W at solar irradiance G=961.90 W/m^2 as shown in Table 3.

The energy flow diagram of the PV module is shown in Fig. 16.

Table 3. Electrical performance of the PV module

Time	**I [A]**	**V [V]**	**Power [W]**	**G [W/m^2]**
9:30	0.95	20.36	19.34	904.76
10:30	1.00	19.69	19.69	952.38
11:30	1.00	19.83	19.83	961.90
12:30	0.99	19.84	19.64	942.85
13:30	0.96	19.82	19.02	904.76
14:30	0.80	20.80	16.64	752.38

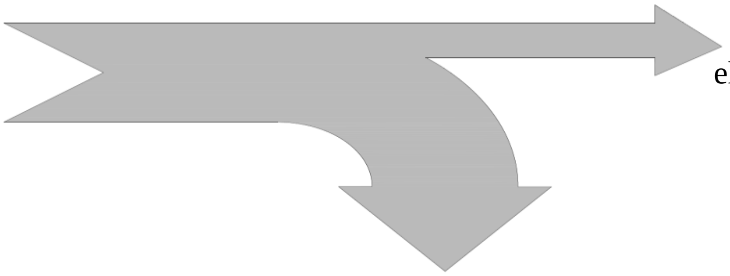

Figure 16. Energy flow diagram of the PV module

The performance of CPV/T collector using two mirrors is shown in Table 4. The table shows the electrical performance along with the inlet (T_{in}) and outlet (T_{out}) temperatures of circulated water and ambient temperature (T_{amb}). The water mass flow rate ($\dot{m}$) from the tap was kept constant.

The energy flow diagram of CPV/T collector with two mirrors is shown in Fig. 17. Although the electrical efficiency is less compared to the PV module, the electrical power was increased by using two and three mirrors. The reasons for the decrease in electrical efficiency were due to the increase in the temperature of the CPV/T collector and losses due to reflection. The efficiency can be increased by improving the cooling system.

Table 4. Performance of CPV/T collector using two mirrors

Time	**I [A]**	**V [V]**	**Power [W]**	**T_{in} [ºC]**	**T_{out} [ºC]**	**T_{amb} [ºC]**	**$\dot{m}$ [kg/s]**
9:30	1.37	22.23	30.45	16	20	15	0.006
10:30	1.35	21.02	28.37	20	24	19	0.006
11:30	1.56	20.87	32.55	19	24	20	0.006
12:30	1.52	21.17	32.17	18	23	21	0.006
13:30	1.34	21.06	28.22	20	24	20	0.006
14:30	0.67	21.36	14.31	19	21	19	0.006

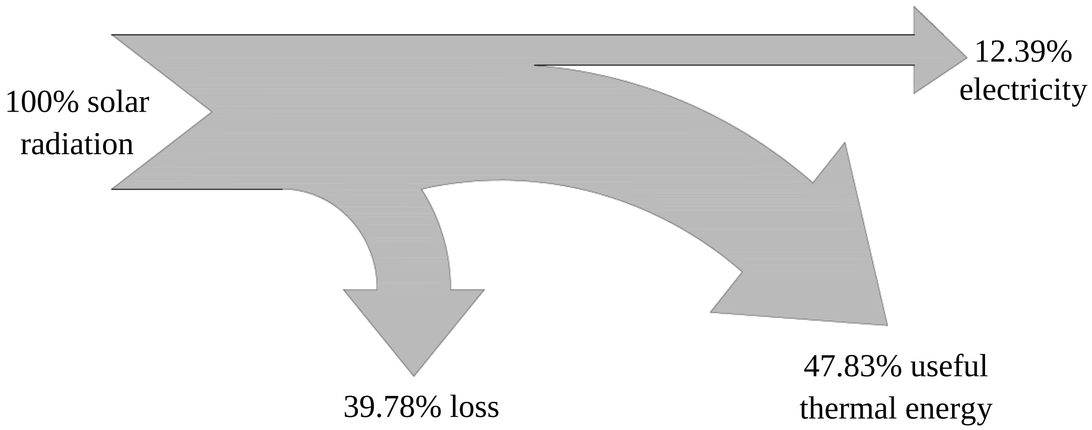

Figure 17. Energy flow diagram of CPV/T collector with two mirrors

The performance of CPV/T collector with three mirrors is shown in Table 5.

The energy flow diagram of CPV/T collector with three mirrors is shown in Fig. 18.

During the day of test, a maximum value of solar radiation was found to be 961.90 W/m^2 and maximum ambient temperature was 21 ^{o}C as shown in Fig. 19.

Table 5. Performance of CPV/T collector using three mirrors

Time	**I [A]**	**V [V]**	**Power [W]**	**T_{in} [°C]**	**T_{out} [°C]**	**T_{amb} [°C]**	**$\dot{m}$ [kg/s]**
9:30	1.95	22.16	43.21	16	22	15	0.006
10:30	2.13	21.37	45.51	20	26	19	0.006
11:30	2.36	21.08	49.74	19	27	20	0.006
12:30	2.24	21.47	48.09	18	25	21	0.006
13:30	2.11	21.44	45.23	20	27	20	0.006
14:30	1.13	21.73	24.55	19	23	19	0.006

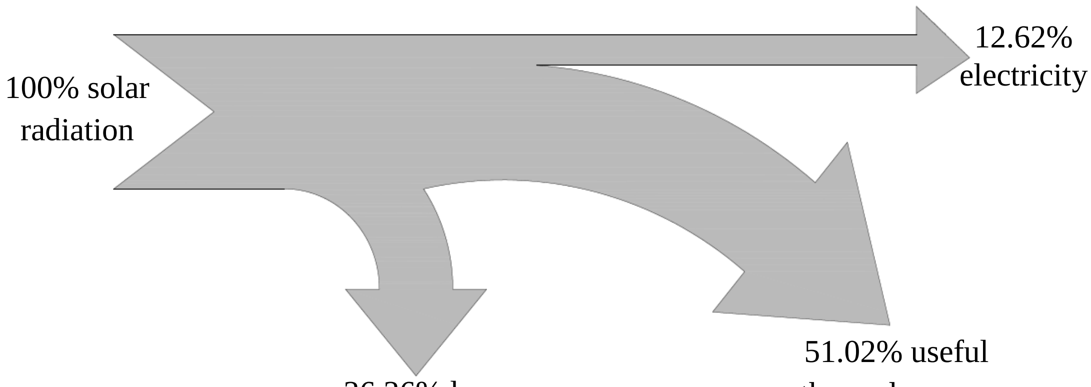

Figure 18. Energy flow diagram of CPV/T collector with three mirrors

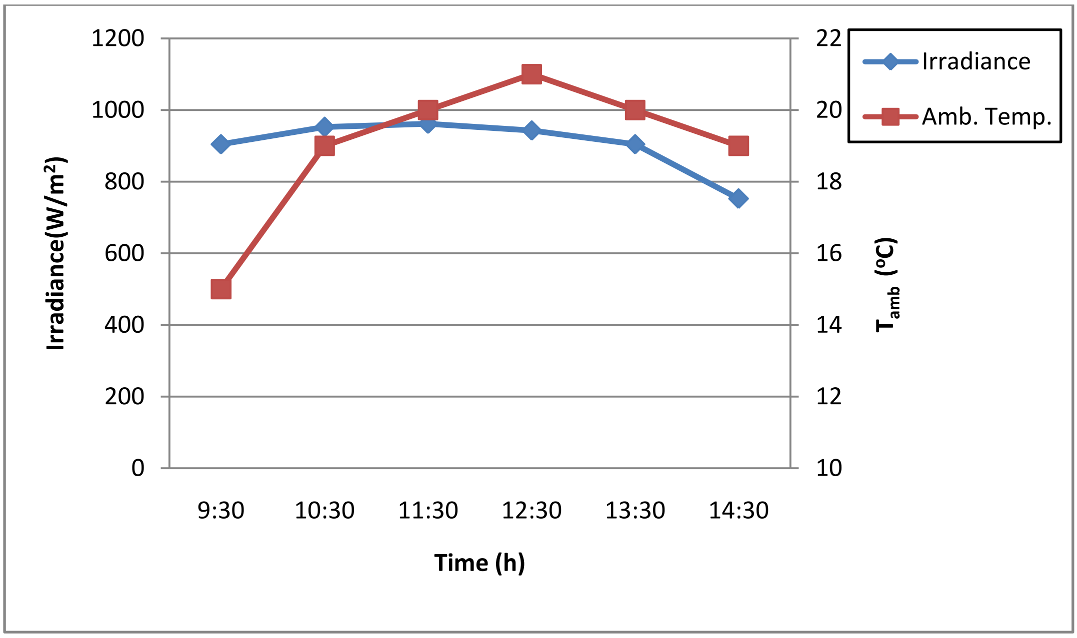

Figure 19. Variation of ambient temperature and solar irradiance during the test day

The short circuit current (I_{SC}) increases as more solar radiation is focused on PV cells of CPV/T collector. The variations of I_{SC} versus time for PV module and CPV/T collector are shown in Fig. 20.

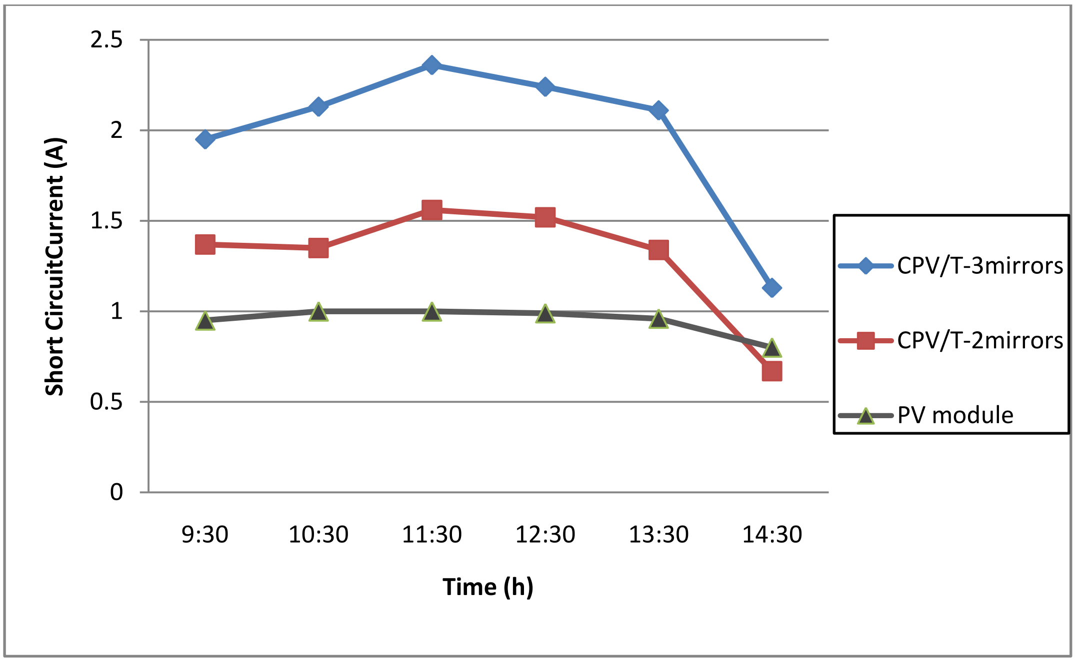

Figure 20. Variation of short circuit current versus time during the day of test

The open circuit voltage (V_{OC}) decreases significantly as the temperature increases, thus the power output decreases about −0.4 to −0.5% due to the increase in temperature. The variations of V_{OC} versus time for PV module and CPV/T collector are shown in Fig. 21.

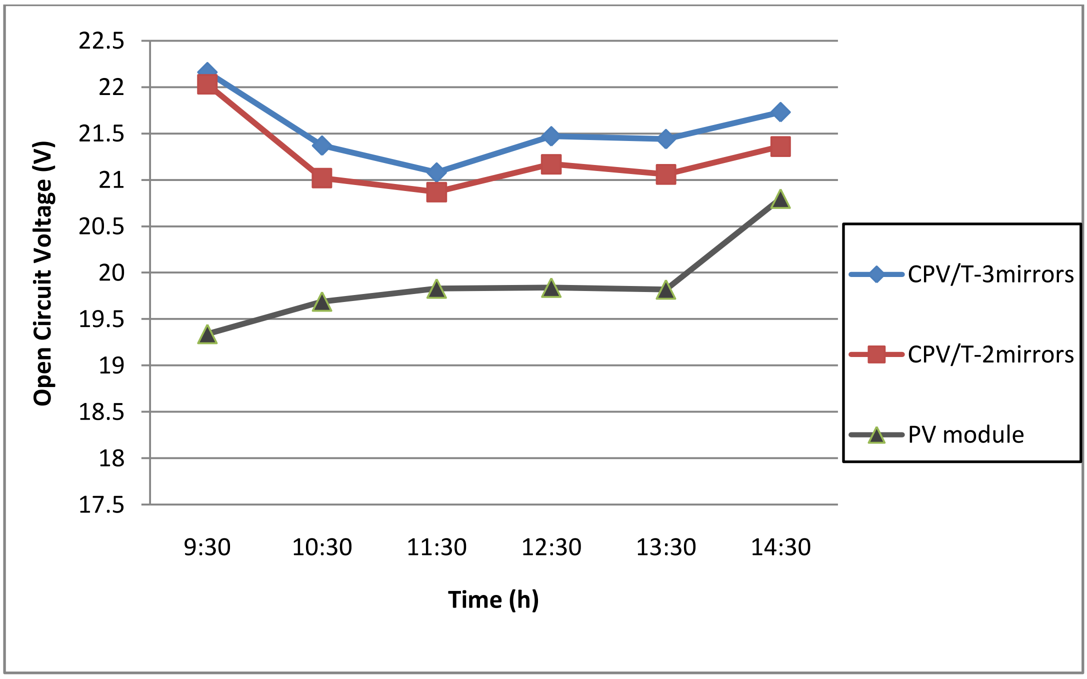

Figure 21. Variation of open circuit voltage versus time during the day of test

The PV cells operate in real outdoor conditions in a temperature range between 40 ^{o}C to 60 ^{o}C [3]. Cooling the CPV/T collector by water can significantly reduce the PV cells operating temperature, therefore increasing the electrical power output.

The power produced by PV cells was calculated using Eq. (3.12). The electrical power outputs generated from the PV module and CPV/T collector during the day of test are shown in Fig. 22. A maximum electrical power output of CPV/T collector using two mirrors was found to be 32.55 W, which is 2.17 times the 15 W rated power of the PV module under standard test condition.

By using three mirrors, a maximum electrical power output of CPV/T collector was found to be 49.74 W, which is 3.3 times the 15 W rated power of the PV module under standard test conditions.

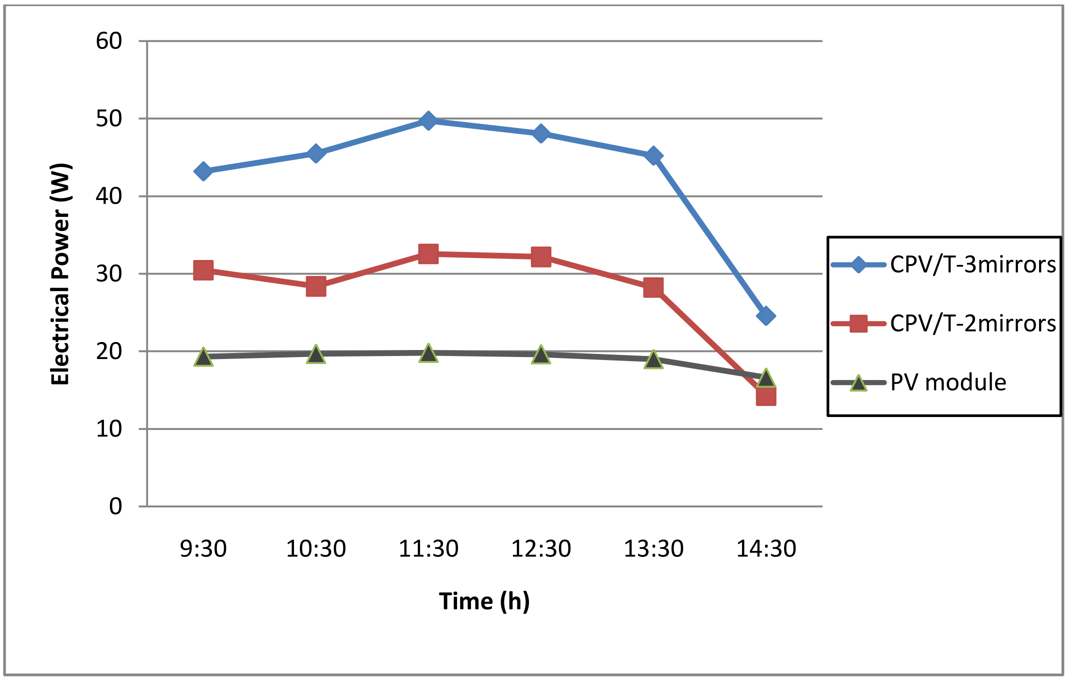

Figure 22. PV module and CPV/T collector electrical power outputs

When mirrors were used, more solar radiation is concentrated onto the PV cells of CPV/T collector. Thus, the electrical and thermal outputs are increased.

The useful thermal energy outputs were calculated using Eq. (3.9) and are shown in Fig. 23. Maximum thermal energy outputs of CPV/T collector using two and three mirrors were found to be 126.23 Wh and 189.35 Wh respectively.

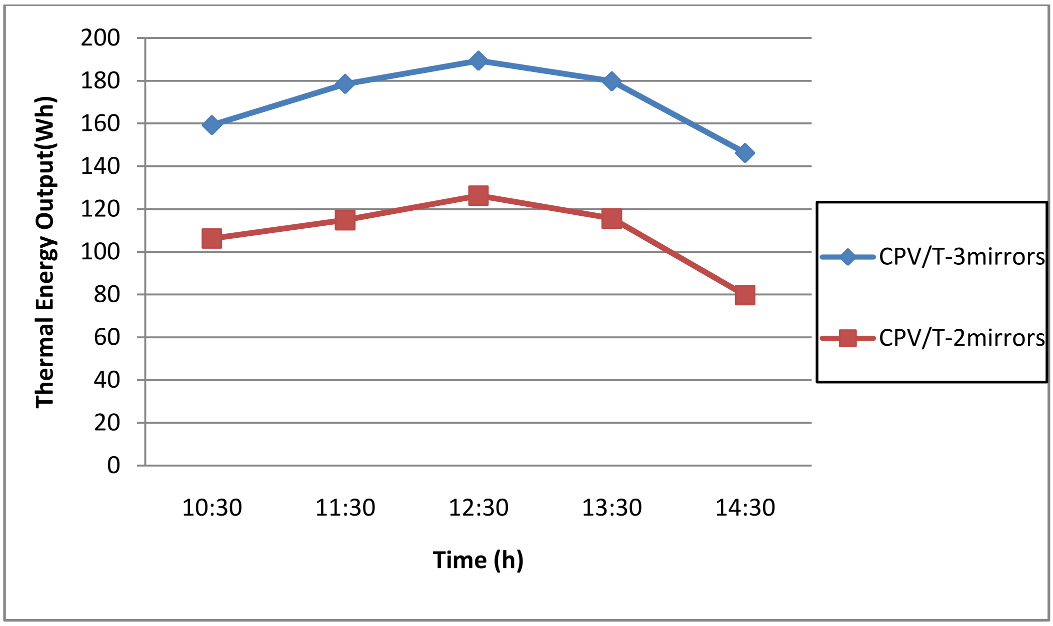

Figure 23. The CPV/T collector thermal energy outputs

The increment in the temperature of circulated water through the CPV/T collector during the day is shown in Fig. 24. Maximum differences in water temperature between the inlet and outlet were found to be 5 and 8 ^{o}C using two and three mirrors respectively. The quality of thermal energy output is considered low due to the small surface area of the CPV/T collector. Generally, the quality can be increased by increasing the difference in water temperature between the inlet and outlet, but this requires bigger collector area.

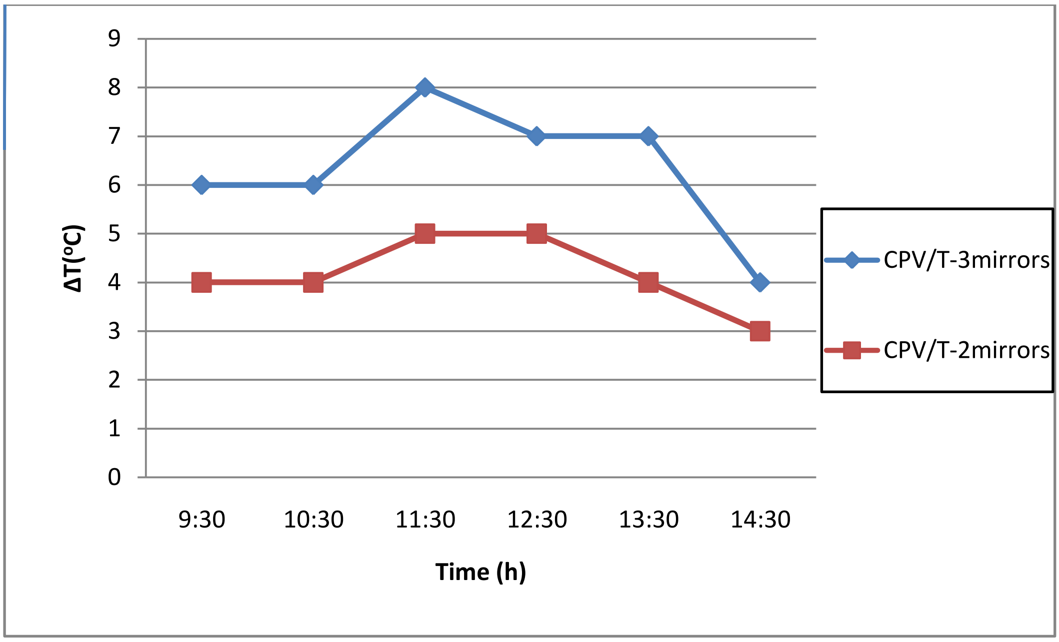

Figure 24. Increment in the temperature of circulated water through the CPV/T collector

Chapter 6

ECONOMIC ANALYSIS

This chapter presents an economic analysis of 5 kW residential PV and CPV/T systems which is usually mounted on the roof.

The PV system capital cost is composed of the PV module cost and the Balance of system (BOS) cost. The BOS cost includes items, such as the costs of the structural system, the electrical system costs, and the battery or other storage system cost in the case of off-grid applications. For residential systems, the minimum BOS and installation costs are about USD 1.6/W [18].

The cost of BOS for 5 kW system = USD 1.6/W × 5000 W = USD 8000

The BOS cost is the same for PV modules and CPV/T collectors.

6.1 Economic Analysis for PV Modules

The 15 W PV module priced at USD 1.33/W, which cost USD 20 in total.

The average electrical power produced under climatic conditions of Northern Cyprus is calculated using data of Table 2, and is found to be 19.02 W.

$$\text{The number of modules should be installed} = \frac{Capacity\ \ of\ residential\ \ system}{PV\ module\ \ electrical\ \ power\ \ output} \qquad (6.1)$$

Thus, the number of PV modules required for 5 kW capacity is 263.

The cost of 263 PV modules is USD 5260.

The total cost of the residential PV system = cost of PV modules + cost of BOS, which is USD 13260.

6.2 Economic Analysis for CPV/T Collectors

A CPV/T collector with three mirrors is used in the analysis. The collector consists of the 15 W PV module plus additional components such as: glass epoxy FR-4, insulation, mirrors, wooden frame, and metal pipes.

The cost of each CPV/T collector is estimated to be USD 40.

The average electrical power produced is calculated using data of Table 4, and is found to be 42.72 W. Therefore, the number of CPV/T collectors required for 5 kW capacity is 117.

The cost of 117 CPV/T collectors is USD 4680.

The total cost of the residential PV system = cost of CPV/T collectors + cost of BOS, which is USD 12680.

$$\text{The annual thermal energy output} = \text{daily output} \times 365 \text{ days} \tag{6.2}$$

$$= 0.189 \text{ kWh} \times 117 \text{ collectors} \times 365 \text{ days}$$

$$= 8071.24 \text{ kWh}$$

The minimum electrical energy price for the domestic sector is USD 0.22/kWh.

The annual savings on thermal energy = 8071.24 kWh × USD 0.22/kWh, which is USD 1775.67.

The savings on 117 CPV/T collector = Total cost − savings on thermal energy (6.3)

= USD 12680 − USD 1775.67

= USD 10904.33

The annual savings on electrical power = system capacity × USD 0.22/kWh (6.4)

= 5000 W × USD 0.22/kWh = USD 1100

The economic analysis of 5 kW residential PV and CPV/T systems is shown in Table 6. The payback period was calculated as:

Payback period = Initial investment / annual savings on electrical power (6.5)

Table 6. Economic analysis of 5 kW residential PV and CPV/T systems

	PV	CPV/T
Initial investment (USD)	13260	10904.33
Annual savings (USD)	1100	1100
Economic lifetime (years)	20	20
Payback period (years)	12.1	9.9

The CPV/T collector has less payback period since the collector is able to provide thermal energy and generates up to treble the electrical power of a PV module.

Chapter 7

CONCLUSION

A concentrating photovoltaic/thermal collector (CPV/T) was constructed by the integration of water cooling system with a PV module and using a set of ordinary flat mirrors to concentrate sunlight onto the collector surface. The performance of the CPV/T collector was investigated experimentally and compared with a PV module used as reference under climatic conditions of Northern Cyprus.

The results of experimental investigation showed that the electrical power output from the CPV/T collector increases as the number of mirrors increased. As water circulated through the collector, useful heat was extracted and the operating temperature of PV cells was decreased, thus electrical efficiency of the module was increased. It was stated that normal PV modules operate well under low concentrations (up to 10 suns). At higher concentrations, specially designed and constructed solar PV cells should be employed. For every sun concentration, the rated power increment of the module was observed.

Using two mirrors, a maximum electrical power output was found to be 32.55 W which is 2.17 times the 15 W rated power of the PV module under standard test condition. When three mirrors were used, the maximum electrical power output was found to be 49.74 W which is 3.3 times the rated power.

Maximum differences in water temperature between the inlet and outlet of CPV/T collector were found to be 5 and 8 ^{o}C using two and three mirrors respectively.

The useful thermal energy outputs were found to be 126.23 Wh and 189.35 Wh using two and three mirrors respectively.

Improving the cooling system in the CPV/T collector leads to an increase in the electrical efficiency and the thermal energy output.

Future work:

A future study will investigate the performance of the CPV/T collector by using different type of concentrator or increasing the number of mirrors. Further work can also be done by combining the collector and the mirrors into one system that is able to track the sun automatically.

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