An-Najah National University

Faculty of Graduate Studies

Performance Analysis of Different Solar Water Heating Systems in West Bank

By

Linda Ahmad Mohammad Mansour

Supervisor

Dr. Imad Ibrik

Co- Supervisor

Dr. Abdelrahim Abusafa

This Thesis is Submitted in Partial Fulfillment of the requirements for the Degree of Master of Clean Energy and conservation Strategy Engineering. Faculty of Graduate Studies, An-Najah National University, Nablus – Palestine.

2019

Performance Analysis of Different Solar Water Heating Systems in West Bank

By

Linda Ahmad Mohammad Mansour

This thesis was defended successfully on 29/09/2019 and approved by:

Defense committee Members		**Signature**
1-Dr. Imad Ibrik	**/ Supervisor**	**………………..**
2-Dr. Abdelrahim abusafa	**/ Co-supervisor**	**………………..**
3-Dr. Afeef Aqel	**/ External Examiner**	**…..……………**
4-Dr. Aysar Yasin	**/ Internal Examiner**	**…..……………**

Dedication

Praise be to Allah, Lord of the worlds

To the spirit of our Prophet Mohammad (Blessings and Peace upon him)

To my Parents

To my brothers and sisters

To my teachers

To all of them,

I dedicate this work

Thank you all

For being a great source of support, inspiration and encouragement

Acknowledgements

Initially, I would like to thank Allah for blessing me with the opportunity to contribute to the research community through this research thesis.

I would like to thank both my university supervisors Dr. Imad Ibrik and Dr. Abdelrahim Abusafa for giving me strong support, inspiration, encouragement and guidance during the thesis.

Many thanks also for my internal examiner Dr. Aysar Yasin and my external examiner Dr. Afeef Aqel.

Also big thanks to my father and mother who have been very understanding and supportive during this thesis. May Allah give them long and healthy life.

My thanks and appreciations for the staff of Clean Energy and Conservation Strategy Engineering Master Program in An-Najah National University.

Finally, I would like to thank everybody who was important to the successful realization of thesis, as well as expressing my apology that I could not mention personally one by one.

الإقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل عنوان:

Performance Analysis of Different Solar Water Heating Systems in West Bank

أقر بأن ما اشتملت عليه هذه الرسالة إنما هو نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، وأن هذه الرسالة كاملة، أو أي جزء منها لم يقدم من قبل لنيل أي درجة أو لقب علمي أو بحثي لدى أي مؤسسة تعليمية أو بحثية أخرى.

Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's name: **اسم الطالب:**

Signature: **التوقيع:**

Date: **التاريخ:**

Table of Contents

List of Tables

List of Figures

List of Abbreviations

Parameter	Value	Unit
FPCs	Flat plate collectors	-
ETCs	Evacuated tube collectors	-
SWHSs	Solar Water Heating Systems	-
S-FPC	Serpentine type flat plate collector	-
P-FPC	Parallel type flat plate collector	-
RE	Renewable Energy	-
PCBS	Palestinian Central Bureau of Statistics	-
PV	Photovoltaic	-
ICS	Integral Collector Storage	-
η_c	Collector efficiency	-
$\dot{Q}_{out}$	Collector heat input	W
$\dot{Q}_{in}$	Collector heat input	W
Q_{in}	Collector heat energy	Wh
A_c	Collector area	m^2
G_t	Intensity of solar radiation on tilted surface of collector	W/m^2
I	Average daily solar radiation on tilted surface of collector	$Wh/m^2/day$
τ	Transmission coefficient	-
α	Absorption coefficient	-
$\dot{m}$	Mass flow rate	kg/s
C_p	Specific heat capacity of water (C_p= 4.2 kJ/kg.°C)	kJ/kg.°C
T_{out}	Collector outlet temperature	°C
T_{in}	Collector inlet temperature	°C
$\dot{Q}_{loss}$	Heat loss	W
U_L	Heat transfer coefficient	W/m^2. °C
T_c	Collector average temperature	°C
T_a	Ambient temperature	°C
F_R	Collector heat removal factor	-
η_{sys}	Efficiency of solar water heating system	-
m	Water mass inside the tank	kg
$\bar{T}$	Average tank temperature	°C
ε	Emittance	-
ϕ	Location latitude	-
Q_u	Useful collected energy by the SWHS	Wh
SPP	Simple payback period	Year
NPV	Net present value	NIS

C	Life cycle cost	NIS
S	Annual saving	NIS
C_0	Fixed cost	NIS
$C_{running}$	Running cost	NIS
E_s	Annual energy savings	kWh
E_{tariff}	Cost per energy unit	NIS/ kWh
R	Revenues	NIS
R_t	Total revenues over project lifetime	NIS
η_o	Maximum system efficiency	-
ER_{min}	Minimum solar radiation needed to rise the water temperature from the T_1 to T_2	kWh/m^2
ESR	Yearly effective solar radiation	kWh/m^2
ER_A	Actual solar radiation of the day	kWh/m^2
ER	Daily solar radiation	kWh/m^2

Performance Analysis of Different Solar Water Heating Systems in West Bank

By
Linda Ahmad Mohammad Mansour
Supervisor
Dr. Imad Ibrik
Co-Supervisor
Dr. Abdelrahim Abusafa

Abstract

This thesis investigates experimentally the energy performance of flat plate collectors (FPCs) and evacuated tube collectors (ETCs), which are the mostly common, used for Solar Water Heating Systems (SWHSs) in Palestine.

A locally made SWHS, with $0.48m^2$ serpentine type flat plate collector (S-FPC), $0.48m^2$ parallel type flat plate collector (P-FPC) and $0.31m^2$ U-Pipe ETC was installed on the rooftop of Energy Research Center building at Al-Najah National University. The three collectors were connected in parallel to one storage tank of 30 Liter capacity.

Water circulation between collectors and storage tank was controlled by valves in away allowed to test only one collector at a time.

Every 15 minutes, data of collector’s inlet temperature, collector’s outlet temperature and tank temperature were collected by means of temperature sensors. The weather data (ambient temperature and solar radiation at tilted plan) were collected also using a meteorological weather station.

The data were gathered for 13 days in May 2019 and June 2019 (4 days for S-FPC, 5 days for P-FPC and 4 days for ETC). The performance of each system were studied separately. Then, three days with the same weather condition were used to compare the performance of the three collectors.

The results show that the daily energy collected by S-FPC is 1015 Wh/m^2, 1415 Wh/m^2 for P-FPC and 1854 Wh/m^2 for ETC. The system efficiencies were 26%, 38% and 49% for S-FPC, P-FPC and ETC respectively.

Economic analysis shows that all SWHSs are economically feasible with Net Present Value (NPV) and simple payback period (SPP) 7660 NIS, 1.56 years for S-FPC, 18400NIS, 1.5 years for P-FPC and 10400 NIS, 5.35 years for ETC.

Chapter One
Introduction

1.1 General background

World Population is currently growing by an estimated average of 82 million per year (Worldometers, 2019), this huge growth of population requires a parallel growth in all aspects of life and continuous developments and improvements to keep on high quality of life. But any new economic or social development relies on energy for production and manufacturing processes.

All countries over the world have used fossil fuels such as coal, oil and natural gas as main energy sources for many decades. This extensive use for fossil fuels led to serious environmental issues, such as air pollution and global warming because burning fossil fuels generates harmful gases.

These issues motivated many countries to decrease their reliance on fossil fuels and to start using renewable energy (RE) sources, especially that the reserves of fossil fuels are limited and will be depleted one day.

RE sources such as solar energy, wind, geothermal heat, water, tides, and waves are naturally replenished, will not run out, clean and have no emissions. Countries that use RE can achieve sustainable development by having secure, reliable and affordable energy sources with effective cost and without damaging the environment.

Globally, statistics show that the total renewable power capacity more than doubled in the decade 2007-2017 as shown in Figure 1.1, but the contribution of RE still shows low percentage from global consumption as illustrated in Figure 1.2.

Figure 1.1: Global renewable power capacity, 2007-2017 (REN21, 2018).

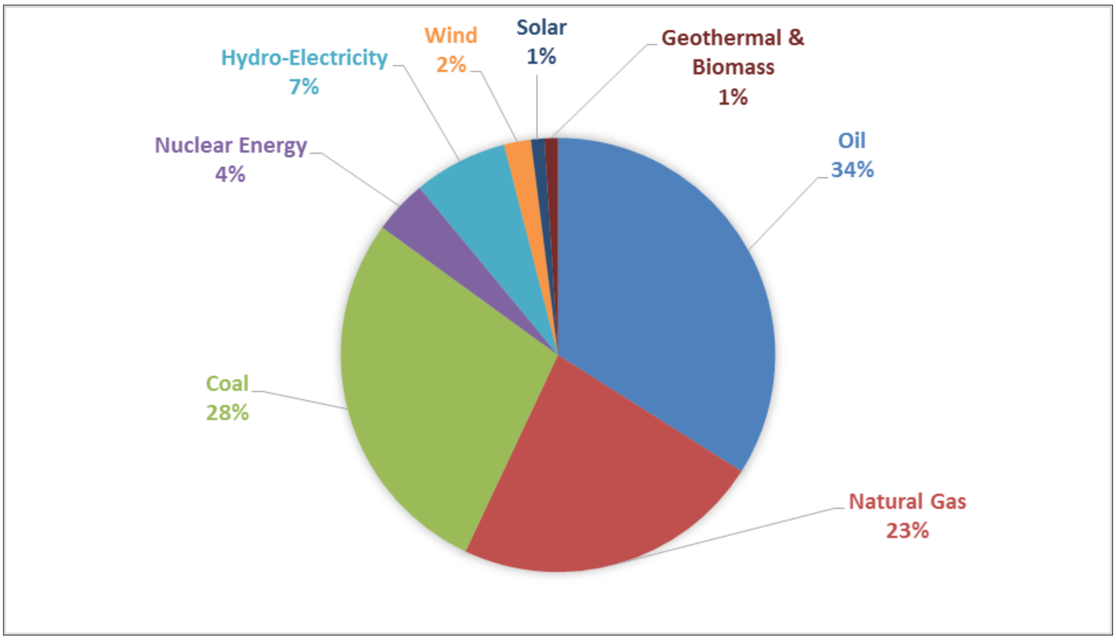

Figure 1.2: Total World Energy Consumption, 2017 (Bp, 2018).

In Palestine, the energy situation is different. Palestine has no natural resources such as coal, oil and gas, so it imports 100% of the fossil fuel and more than 90% of electricity from neighboring countries especially from Israel, as shown in Table 1.1. The political restrictions that have been imposed by Israel prevent Palestine from the independence in energy sector, building its own power generation plants and open trade in electricity and oil products with other countries (Juaidi et al., 2016). The Israeli control on energy sources, prices and quantities limits the development in all aspect of Palestinian life.

Table 1.1: Quantity of electricity imported and purchased in Palestine by source, 2017 (adapted from (PCBS, 2017)).

Quantity of electricity imported and purchased in Palestine by source, 2017 , (in MWh)					
Total	Source				
	Purchased from Palestine Electric Company	Imported			
		Total	Jordan	Egypt	Israeli Electricity Company
5,945,871	369,007	5,576,864	54,229	61,480	5,461,155

To overcome the energy problem, and to obtain secure, reliable and affordable energy, the Palestinian government put the General Renewable Energy Strategy in 2012, aiming for 10% of total domestic energy production and 25% of total energy consumption to come from renewable sources by 2020.

By referring to Figure 1.3, it can be noticed that 50% of the RE that used to achieve the General Renewable Energy Strategy is covered by solar energy; this is because solar energy is the most available RE in Palestine that can be exploited in commercial quantities and reasonable prices.

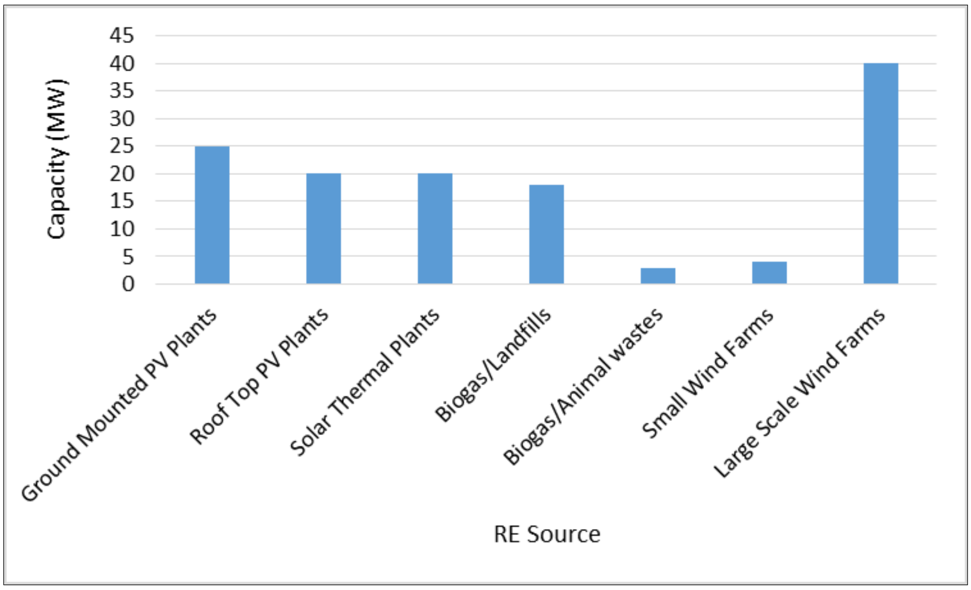

Figure 1.3: General Renewable Energy Strategy (PERC, 2019).

Palestine has high potential of solar radiation, where the average annual sunshine hours exceeds 3000 h and the average global solar radiation is 5.4 $kWh/m^2/day$. This makes solar energy a reliable source that can be used in electrical and thermal applications, and helps the Palestinian community to produce their own energy and get rid of Israeli control on electricity and fuel resources.

In 2017, the share of solar energy contribution is approximately 28% of the imported and produced electrical energy, and 7.24% of the total consumed energy in Palestine in 2017 (PCBS, 2017).

Palestinians have used solar energy for producing electricity through photovoltaic (PV) solar panels many years ago. PV Solar was used in small scale Off Grid projects, especially in rural villages that were not connected to grid, but it was started to be used seriously after putting the General Renewable Energy Strategy by the Palestinian government in 2012 in form of small and large scale On Grid projects.

The other more familiar application for solar energy is heating water by means of Solar Water Heating Systems (SWHSs) which have been used extensively in Palestine, such that 56.5% of Palestinian families are using it, (PCBS, 2015). Palestine is ranked sixth among the top ten countries in the world in the use of SWHSs as clear in Figure 1.4.

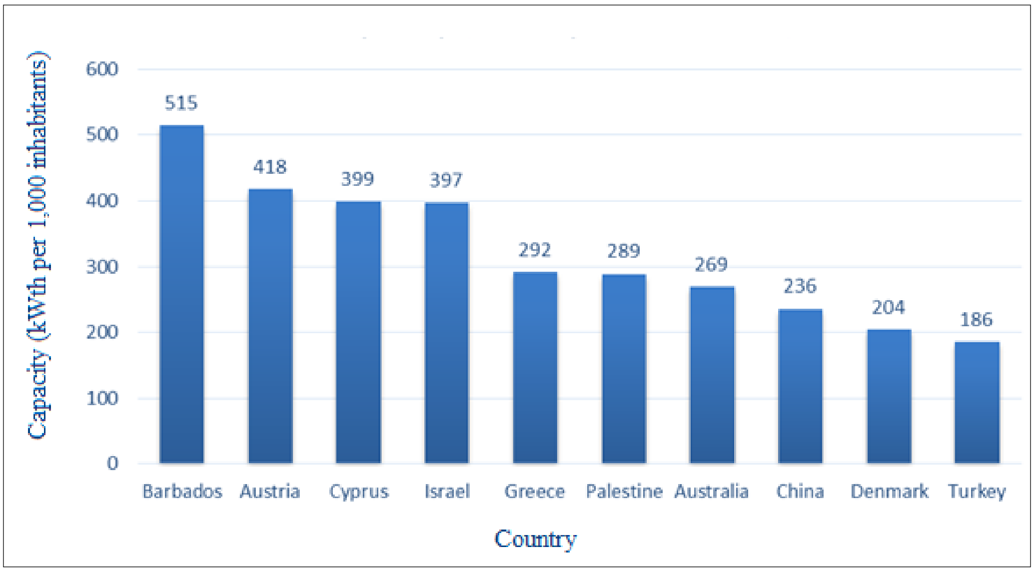

Figure 1.4: Top 10 countries of cumulated water collector installations – 2016 (Weiss, 2018).

Two types of SWHSs are commonly used in Palestine. The first and the most widespread type is with FPC, which is extensively used not only on household but also in schools, hospitals, factories and many other facilities.

The total flat plate collector area in operation in Palestine by the end of 2016 was 1,826,625 m^2 (Weiss, 2018).

The second type is with ETC. ETCs have started to gain market shares with total collectors area in operation by the end of 2016 was 8,225 m^2 (Weiss, 2018).

We notice a big difference in the total installed area between the two types of collectors, this was because the ETC considered as new technology entered the Palestinian market and because of its high initial cost. But in some cases it has become obvious that low prices were also accompanied by low quality in different respects. Unfortunately, the low quality wasn't always revealed due to the absence of quality and performance tests for the collectors which available in the market even for the installed systems.

High quality , good performance and high efficiency of SWHS means more energy production and less dependency on conventional energy sources for heating water, and due to the fact that 18% of our total used energy goes for water heating (Juaidi et al., 2016), all required tests must be performed to insure that the installed SWHSs are with the highest efficiency .

This study, therefore, aims to build three types of collectors systems (S-FPC, P-FPC and ETC) installed side by side, then to be tested under the weather conditions of West Bank in order to evaluate the actual efficiencies experimentally.

1.2 Research objectives:

The main objectives of this research are:

1. Studying the performance of three types of thermosiphon solar water heating systems, which are the P-FPC, S-FPC and ETC systems.

2. Studying the effect of ambient conditions on the thermal behavior of the three types of SWHSs.

3. Comparing between the efficiency of the three types of SWHSs.

4. Investigating the economic benefits from using each type of SWHSs.

1.3 Research Problem

SWHSs are commonly used in West Bank, and because of that a lot mega-watts are saved yearly. Therefore, the use of high efficient and cost effective SWHS is necessary to save as much as of energy and get rid of conventional energy sources as possible.

Palestine lack any test labs, certification system, quality control regulations and rules aimed at SWHSs, so we don’t have enough information about the efficiency or thermal performance of the installed systems.

The aim of this research is to study the thermal performance of the common used types of SWHSs in West Bank and to find the efficiency and the economic feasibility of each type.

1.4 Research Questions

1- What is the effect of ambient conditions on the thermal performance of P-FPC, S-FPC and ETC systems?

2- What is the efficiency of each type of SWHSs?

3- Which system has more efficiency than others, at the same weather conditions?

4- What is the simple payback period and net present value of each type of SWHSs?

Chapter Two

Solar Water Heating Systems

2.1 Introduction

SWHSs provide environmentally friendly heat for household water heating, space heating, and the heating of swimming pools. Such systems capture and retain heat from the sun and transfer this heat to a fluid. Then the fluid transfers solar heat directly or indirectly to your home, water, or pool.

Figure 2.1 shows the schematic diagram for typical domestic SWHS, which mainly consists of solar collector, insulated storage tank, heat exchanger and pipes. Also shown is an electric circulation pump, control and safety equipment, which may be powered by a PV Module, so the system doesn't rely on external energy source for operation.

Basic system operation includes the pump circulating a heat transfer fluid, typically water or water/glycol mix, through the solar collector for heating. This hot liquid then passes through a heat exchanger in the storage tank where it warms up cold feed water and cycles back to the collector. The cold feed water remains in this storage tank, constantly being heated while the system is operational. As hot water is drawn from the storage tank, it is replenished with cold water.

Many systems also have a back-up heater to ensure that all of a consumer’s hot water needs are met even when there is insufficient sunshine.

By this way, SWHS can be used as a heater or pre-heater that ensures a constant supply of hot water at the desired temperature, and reduce dependency on conventional means of heating that depends on fossil fuels.

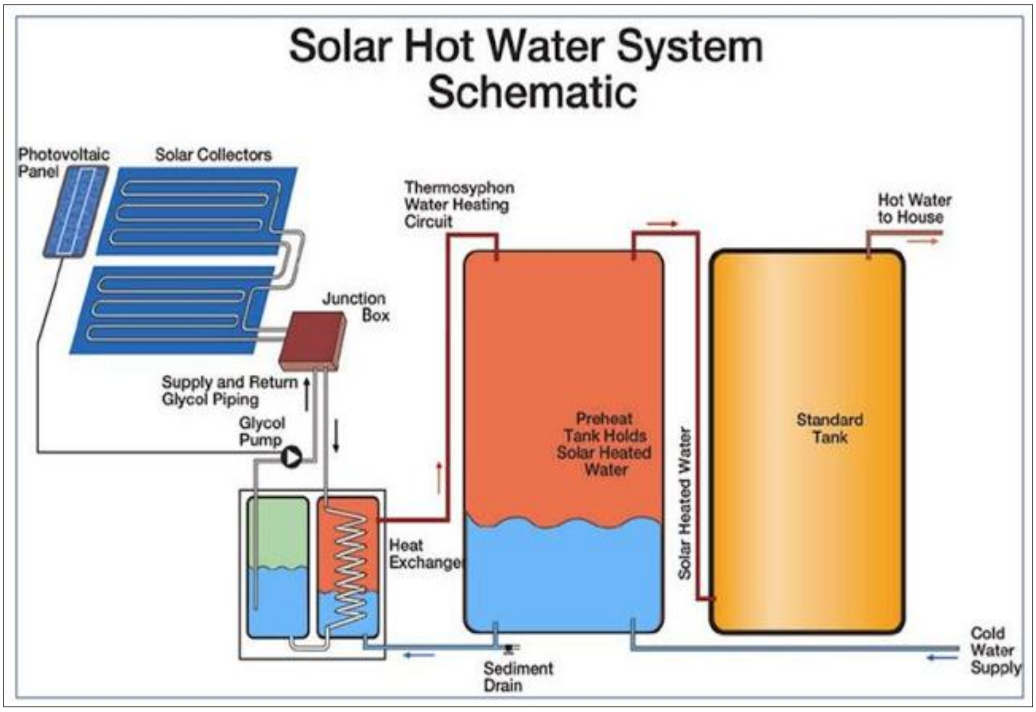

Figure 2.1: Schematic diagram for typical solar domestic water heating system (Slide Share, 2016)

2.2 Solar collectors

This device is the major component in any SWHS. It absorbs solar radiation, converts it into heat, and transfers the heat to the fluid that flowing through it. This heat can be used for heating water, space heating or swimming pool heating.

Solar collectors are divided into three types, flat plate collectors, evacuated tube collectors, and concentrating collectors.

The following sections review the different types of solar collectors:

2.2.1 Flat plate collector

Figure 2.2 shows the typical glazed FPC, it is a waterproof, well-insulated metallic box covered on top with glass sheet. It contains a dark metallic absorber plate (selectively coated) with built in small vertical copper tubes called risers contain the heat transfer fluid, usually water. The risers are connected at both ends (top and bottom) to horizontal pipes with large diameter called Headers. The underside of the absorber plate and the side of casing are well insulated to reduce heat losses.

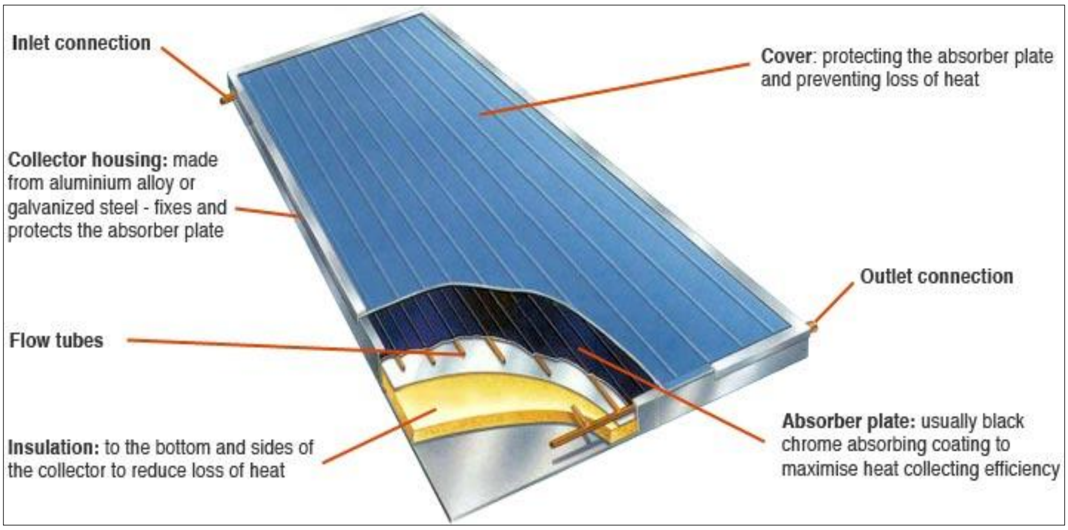

Figure 2.2: Typical flat plate solar collector (Gautam et al., 2016)

The glazing cover is used to protect the enclosed absorber plate and to create an insulating air gap. It is usually made of low-iron tempered glass with high transmittance, it does not absorb the suns thermal energy to any significant extent so the most of the incoming radiation is received by the absorber plate.

When solar radiation passes through the glass cover, it is absorbed by the air gap between the plate and glazing material and prevented from escaping back into the atmosphere. Heat-transfer fluid flows into the collectors' bottom header, and travels up the risers, collecting heat from the absorber plate (some heat lost to the surroundings), and then exits the collector out of the top header.

The FPCs are sorted into two types based on the tubing configuration. They are the parallel configuration and serpentine configuration.

1- Parallel configuration:

The parallel configuration of FPC is the one that shown in Figure 2.3.

It has small parallel tubes (risers) connected at top and bottom to larger tubes (Headers).

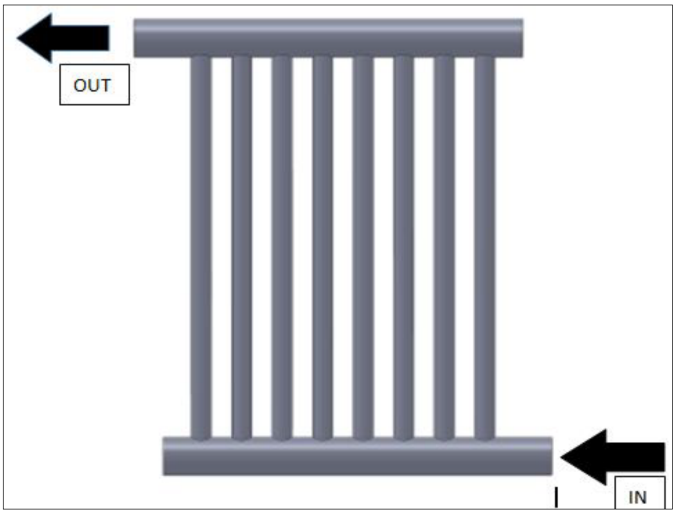

Figure 2.3: Model of parallel tube.

In Parallel configuration, the pressure is higher at bottom of the collector and lower at top. The disadvantages of this model that the fluid pressure and then the flow rate are moderate at the middle where most of the heat is concentrated.

2- Serpentine configuration:

Figure 2.4 shows that the serpentine model has one long continuous tube. The working fluid flows uniformly from bottom to the top of the collector, which means uniform heat transfer to the fluid.

Serpentine configuration is easier to construct compare to parallel which have many welding joints. The probability of fluid leakage in parallel configuration is high compare to serpentine configuration.

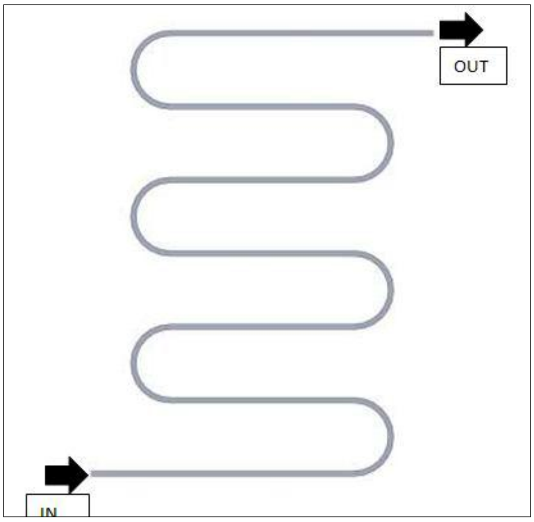

Figure 2.4: Model of serpentine tube.

FPC is installed in a fixed angle, directly towards the Equator, facing south in the northern hemisphere and north in the southern. The optimum tilt angle of the collector is equal to the absolute value of site latitude or site latitude plus 15^o (Yasin, 2017).

For domestic water heating, the FPC can heat the water up to 50°C (Sadaq et al, 2015).

In Palestine, the FPC is the most common type of collectors used in SWHS. It extensively used in residential sector, where about 56.5% of households are using it, because it has a simple design, cheap price and long life period reaches 25 years.

Figure 2.5 shows a schematic drawing of the heat flow through a FPC. There are 80% of the sun heat energy is absorbed in the collector plate. The radiant heat reflects and heat loss in the collector surface is around 10–35% (Hossain et al, 2011).

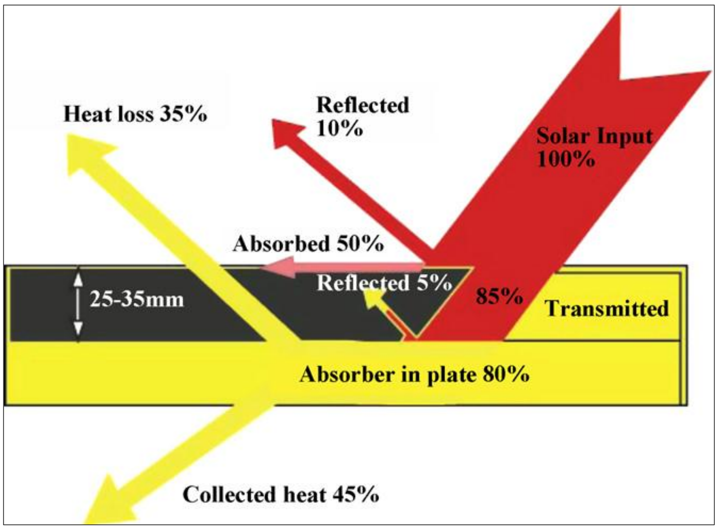

Figure 2.5: Heat flow through a flat plate solar collector (Struckmann, 2008).

2.2.2 Evacuated tube collector

ETC is made of parallel evacuated glass pipes, each evacuated pipe consists of two tubes made from extremely strong borosilicate glass, one is inner and the other is outer tube. The two tubes are fused together on top and the existing air between the two layers of glass is pumped out which form a vacuum between these two layers. The outer tube is transparent while the inner tube coated with a special selective coating, which features excellent solar radiation absorption, (see Figure 2.6 and Figure 2.7). Solar radiations pass through the transparent outer tube and are absorbed by the inner tube. The inner tube gets heated and this heat kept inside because the vacuum allows solar radiation to go through, but doesn’t allow the heat to transfer, the vacuum also works as insulator reducing any heat loss to the surrounding either through convection. By this way the ETC can collect the heat efficiently even in cold weather when FPC performs poorly due to heat loss. The ETC efficiency reaches 70%.

Figure 2.6: Evacuated Tube (Apricus-solar, 2013).

Figure 2.7: Evacuated tube solar collector (Alternative energy tutorials, 2019).

ETC can heat water to a higher temperature than the FPC, it is between 80 - 170 C^{o}, which is making it suitable for commercial and industrial heating applications and for cooling applications (by regenerating refrigeration cycles). While for domestic hot water heating, FPC tends to offer a cheaper and more reliable option.

There are many configurations for ETCs that determine how the fluid circulated around the collector and getting heated. The most common types (water in glass, heat pipe and U-pipe configurations) are reviewed as the following:

2.2.2.1 Water in glass evacuated tube Collector

Water-in-glass ETC consists of glass vacuum tubes inserted directly into a storage tank, with water in direct contact with the absorber surface**.** The heat transfer in this collector is driven by natural circulation of water between the collector and the tank. Water in the tubes is heated by solar radiation, which then rises along the top of the tube to the storage tank and is replaced by cold water from the tank as shown in Figure 2.8.

Water-in-glass ETC is widely used especially for residential applications because of its simple design and low cost.

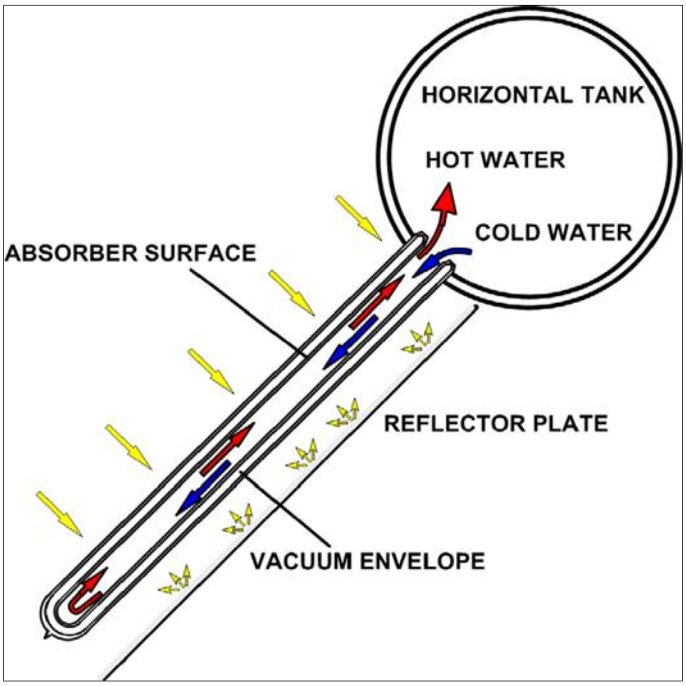

Figure 2.8: Natural circulation in water-in-glass collector (Budihardjo et al, 2007)

2.2.2.2 Heat pipe evacuated tube collector

Heat pipe ETC contains a hollow copper heat pipe attached to an absorbing plate within the vacuum sealed tube. This heat pipe evacuated of air and contains a small quantity of a low pressure alcohol or purified water liquid plus some additives to prevent corrosion or oxidation, see Figure 2.9.

The vacuum within the pipe enables the liquid inside it to vaporize at very lower temperatures than it would normally at atmospheric pressure. When the solar radiation hits the surface of the absorber plate inside the tube, the liquid in the heat pipe quickly turns into a hot vapor and rises up to the top portion of the pipe heating it up to a very high temperature.

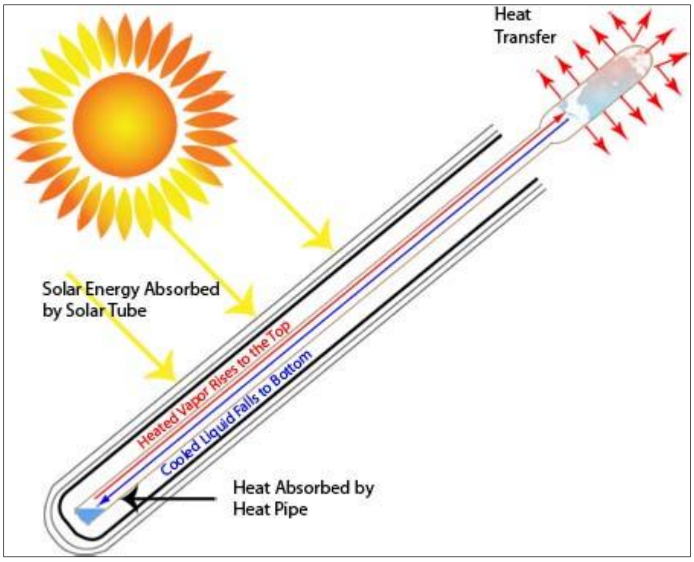

Figure 2.9: Heat pipe evacuated tube (Solar panels plus, 2014).

A copper heat exchanger (Manifold) contains a flowing water or glycol fluid is connected to the top part of the heat pipe, and therefore the evacuated tube. The Fluid inside the manifold extracts the heat energy of the vapor through the heat pipe. The hot vapor losses its energy and condenses back from a gas to a liquid flowing back down the heat pipe to be reheated again. This process continues, as long as the sun shines.

The heat pipe ETC must be mounted in a tilt angle not less than 30^{o} to allow the internal liquid of the heat pipe to return back down to the bottom of the tube.

2.2.2.3 U-pipe evacuated tube collector

U pipe ETC has two copper heat pipes run down and back, inside the tube. Water circulates through the pipes, one for inlet fluid and the other for outlet fluid. The two tubes connected to others at the bottom of the tube as shown in Figure 2.10.

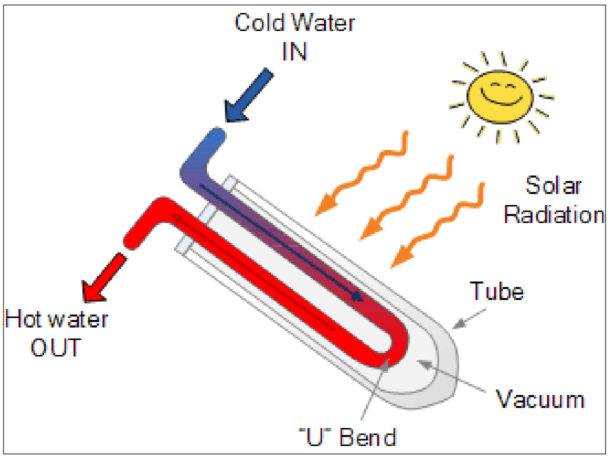

Figure 2.10: U tube collector (Alternative energy tutorials, 2019).

Through this review for the different types of ETCs, it can be noticed that the heat pipe collectors and U pipe collectors have the advantage of the dry connection between the vacuum tube and the absorber, not as water in glass collectors. So if an evacuated tube break, the individual tube can be exchanged without emptying or dismantling the entire system. This flexibility makes heat and U pipe ETC ideal for closed loop solar designs as the modular assembly allows for easy installation and ability to easily expand by adding as many tubes as needed.

On the other hands, the U pipe and water in glass evacuated tube designs are more energy efficient than heat pipe designs, because there isn't a heat exchange between fluids.

2.2.3 Concentrating collectors

Concentrating collectors are a parabolic reflector that concentrate the solar energy onto a receiver in order to heat the heat transfer fluid. Concentrating collectors can be divided according to geometric forms onto four categories as below:

1. Parabolic trough collector.
2. Linear concentrating Fresnel collector.
3. Central receiver system.
4. Parabolic dish collector.

Concentrating collectors provide energy at temperatures higher than those of FPCs and ETCs (Sarbu and Sebarchievici, 2017) which make them more suitable for industrial applications.

2.3 Solar water heating system types

Solar water heating systems are classified according to how water flows through the collector into passive and active systems. Where the passive solar water heating systems rely on natural conviction to circulate the water through the collector to the storage tank. While in active systems, pumps are used to circulate the water through the system.

Active and passive systems can be either direct or indirect systems according to how the water getting heated.

In direct systems water is heated directly as it flows through the solar collector while the indirect systems heat up the water through heat exchanger.

2.3.1 Passive Systems

There are two types of passive systems used, which are:

2.3.1.1 Thermosiphon system

The principle of working for thermosiphon systems depends on the difference in density between hot and cold water. That is, when the sun radiation heats up the water inside collector tubes, it expands and becomes lighter (lower density) than the cold water in the solar storage tank that mounted above the collector. Gravity pulls the cold water down from the tank into collector inlet and pushes the hot water through the collector outlet to the top of the tank. This process continued until the water in the tank reaches equilibrium temperature. The configuration of thermosiphon system illustrated in Figure 2.17.

The consumer uses hot water from the top of the tank, which is replaced by cold water from the bottom of the tank.

Thermosiphon systems are widely used in flat plate and evacuated tube domestic solar water heaters, which make them simple and cheap since no pumps used and no electricity needed and this leads to low maintenance system.

The problem in thermosiphon systems that it is not efficient due to slower water flow rates especially in cold weather, when the temperature difference is low between the water in the tank and in the collector tubes.

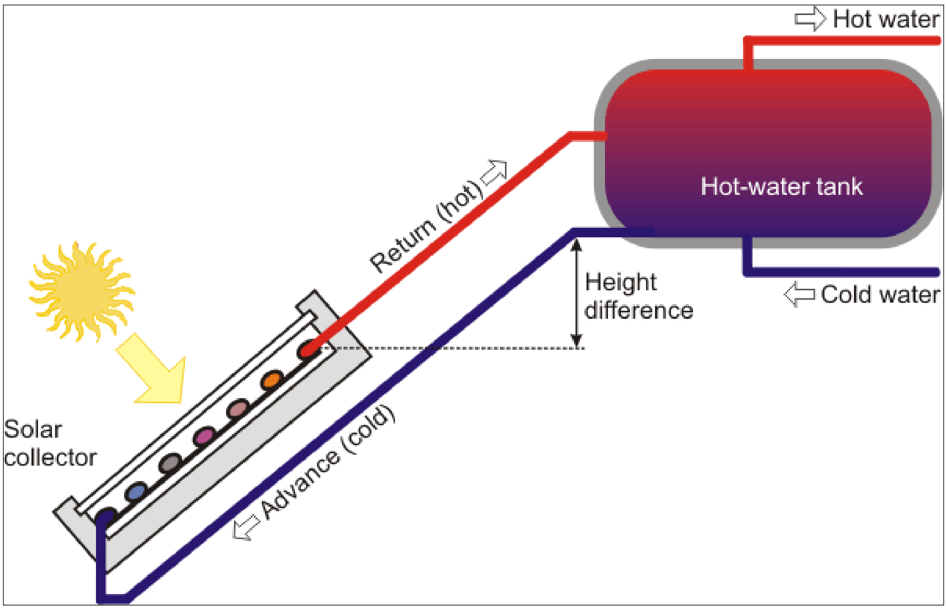

Figure 2.11: Thermosiphon system (Appropedia, 2007).

2.3.1.2 Integral collector storage system

Integral Collector Storage (ICS) or Batch system is known with its simple design since the storage tank and the collector integrated in one single unit.

As we see in Figure 2.18, the Batch system consists of large diameter copper tubes or tanks inside insulated glazed box. The water inside the collector heated by convection and flows upon consumer need to an auxiliary storage tank depending on local main water pressure and it is replaced by cold water without need for a pump.

ICS systems have many disadvantages such as the high weight because the collector and the storage tank are composed in one unit and the heat loss during night or cold weather, besides the problem of water freezing during winter.

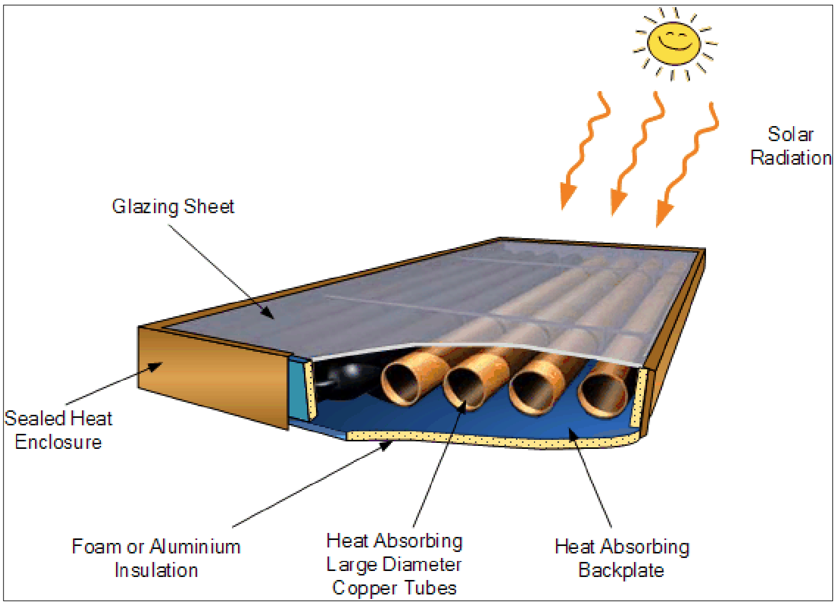

Figure 2.12: Integral Collector Storage Systems (Alternative energy tutorials, 2019).

2.3.2 Active systems

2.3.2.1 Direct active system

Direct active system is the same as thermosiphon system; the difference here is the use of electric pump to circulate the water between the collector and the storage tank. Figure 2.19 shows the typical direct active solar water heater.

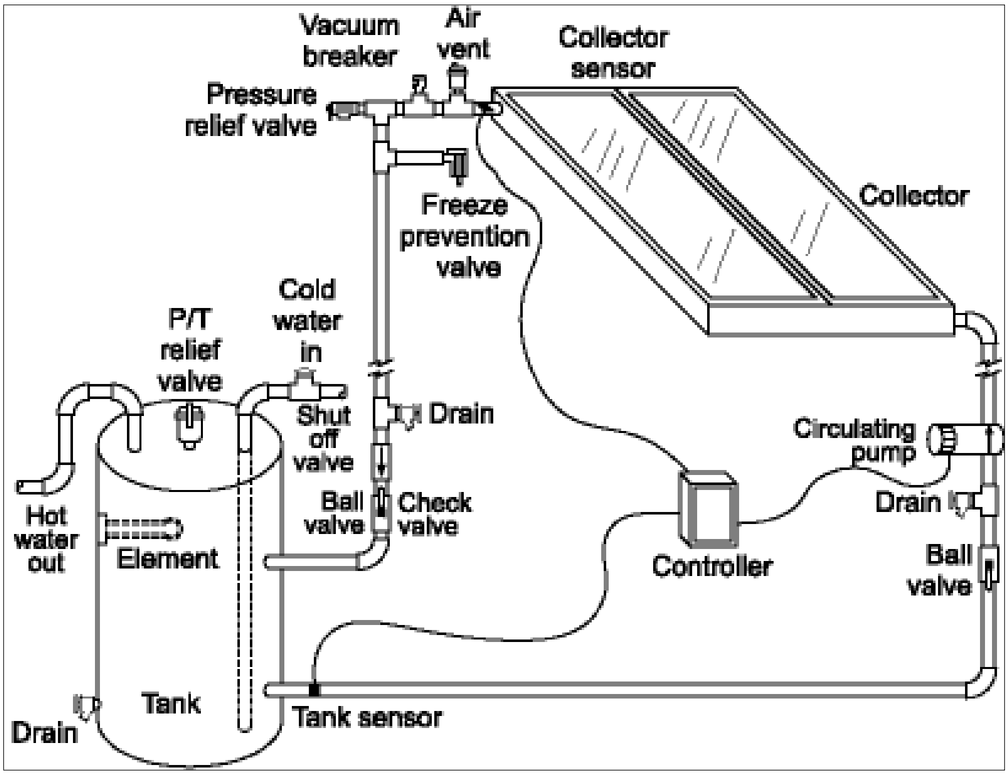

Figure 2.13: Direct Active solar water heater (Mohammed et al, 2011)

2.3.2.2 Indirect active system

Indirect or closed loop active system uses a pump to circulate the heat transfer fluid through the collector and heat exchanger. The heat transfer fluid transfers the heat to the water through the heat exchanger as shown Figure 2.20. Hot water is stored in the tank until needed.

An Antifreeze Glycol is used as a heat transfer fluid in such systems, which is making the indirect active systems suitable for climates of freezing temperatures.

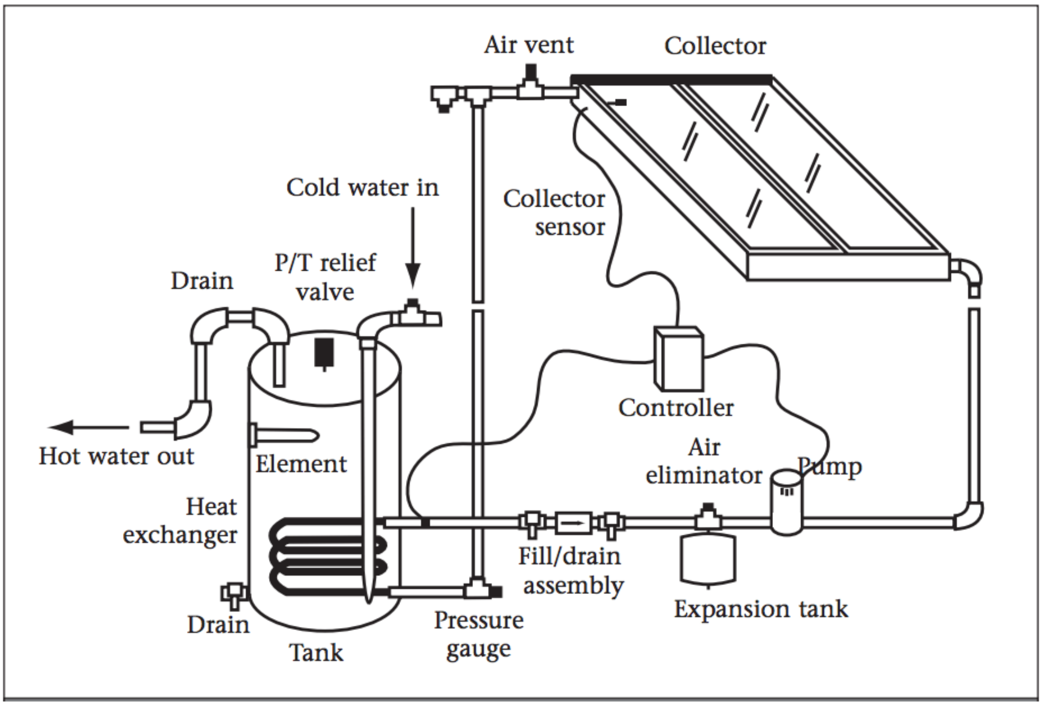

Figure 2.14: Indirect Active systems (Wisehomedesign, 2017).

2.4 Thermal performance of SWHS

The thermal performance of the SWHS can be evaluated by calculating the collector efficiency and system efficiency.

Collector efficiency can be shown in the equation as follows:

$$\eta_c = \text{Collector heat output} / \text{Collector heat input} = \dot{Q}_{out}/\dot{Q}_{in} \quad \text{.............} \quad (1)$$

$\dot{Q}_{in}$ refers to the amount of solar radiation received by collector plan, which can be expressed by:

$$\dot{Q}_{in} = A_c \times G_t \quad \text{..} \quad (2)$$

Where: A_c is the collector area in (m^2) and G_t is the Intensity of solar radiation on tilted surface of collector in (W/m^2).

But due to the fact that some of the solar radiation reflected to the sky and absorbed by the glazing material a conversion factor is used to indicate the percentage of solar radiations transmitted through the collector transparent cover and the percentage being absorbed. This conversion factor is the product of the rate of transmission of the cover (τ) and the absorption rate of the absorber (α).

Thus,

$$\dot{Q}_{in} = A_c \times G_t(\tau\alpha) \quad \text{..} \quad (3)$$

The rate of extraction of heat from the collector ($\dot{Q}_{out}$) can be measured by means of the amount of heat transmitted to the fluid passed through it, that is:

$$\dot{Q}_{out} = \dot{m} \times C_p \times (T_{out} - T_{in}) \quad \text{..} \quad (4)$$

Where: $\dot{m}$ is the mass flow rate of water in (kg/s), C_p is the specific heat capacity of water = 4.2 kJ/kg.°C, T_{out} is the water temperature at collector output in (°C) and T_{in} is the water temperature at collector inlet in (°C).

$\dot{Q}_{out}$ can be expressed also by the difference between of heat received by the collector heat loss to the surrounding.

$$\dot{Q}_{out} = \dot{Q}_{in} - \dot{Q}_{loss} \quad \text{...(5)}$$

As the collector absorbs heat, its temperature (T_c) is getting higher than the ambient temperature (Ta) so it will lose heat to the atmosphere by convection and radiation. The rate of heat loss ($\dot{Q}_{loss}$) depends on the collector overall heat transfer coefficient (U_L) and the collector temperature (Struckmann, 2008).

$$\dot{Q}_{loss=} U_L \times Ac \times (T_c - T_a) \quad \text{...(6)}$$

Then, Q_{out} will be:

$$\dot{Q}_{out} = A_c \times G_t\ (\tau\alpha) - U_L \times A_c \times (T_c - T_a) \quad \text{.......................................(7)}$$

As it is difficult to find the average collector surface temperature, it can be replaced by the collector inlet temperature (T_{in}) if the collector heat output is multiplied by a heat removal factor (F_R).

$$\dot{Q}_{out}= F_R A_c[G_t\ (\tau\alpha)-U_L(T_{in}-T_a)] \quad \text{...(8)}$$

The maximum possible useful heat gain in a solar collector occurs when the whole collector is at the inlet fluid temperature (Struckmann, 2008).

The heat removal factor (F_R) can be expressed also by:

$$F_R = (\dot{m} \times C_p \times (Tout\text{-}Tin))/ (Ac[Gt (\tau\alpha)\text{-}U_L(Tin\text{-}Ta)]) \quad \text{………......…….(9)}$$

Collector efficiency can be calculated using equation (8) as below;

$$\eta_c = \dot{Q}_{out}/[A_c x G_t] \quad \text{………………………………………………….(10)}$$

$$\eta_c = F_R A_c[G_t (\tau\alpha)\text{-}U_L(T_{in}\text{-}T_a)]/ [A_c x G_t] \quad \text{……………………………….(11)}$$

Or;

$$\eta_c = F_R(\tau\alpha)\text{-} F_R U_L [(T_{in}\text{-}T_a)/G_t] \quad \text{…………………………………………(12)}$$

Also can be expressed by the following equation;

$$\eta_c = [\dot{m} x\, C_p\, x(T_{out}\text{-}T_{in})]/[A_c x G_t] \quad \text{………………………………………(13)}$$

While the system efficiency expressed by:

$$\eta_{sys} = (\int_{t1}^{t2} Qu\, dt)/(Ac \int_{t1}^{t2} Gt\, dt) \quad \text{………………………………………(14)}$$

Q_u is the useful heat energy collected the SWHS and equals to (Pei et al, 2012):

$$Q_u = m\, C_p \frac{d\bar{T}}{dt} \quad \text{…………………………………………………………(15)}$$

Where: m is the water mass inside the storage tank in (kg), $\bar{T}$ is the average tank temperature respectively in (°C) and C_p is the Specific heat capacity of water (4.2 kJ/kg.°C).

2.5 Factors affecting the performance of SWHS

The performance of a SWHS depends on the following factors:

2.5.1 Ambient conditions:

The amount of incident radiation determines the absorbed solar radiation by the collector while the ambient temperature determines the thermal losses from the collector. Cloudy conditions limit the beam insolation levels and thus the radiation absorbed by the collector especially the concentrating collectors.

2.5.2 Collector orientation and tilt angle

Orientation and tilt Angle affect the amount of solar radiation received by collector.

Depending on the geographical location, the collector orientation and tilt angle is decided. The optimum orientation for the collector is directly towards the Equator. Facing south in the northern hemisphere and north in the southern. The optimum tilt angle of the collector is equal to the absolute value of the latitude or latitude of the site plus 15^o (Yasin, 2017).

2.5.3 Mass flow rate

The thermal performance of SWHS depends on the flow rate through the collector, the collector efficiency increases as the flow rate and the incident solar radiation increase. Therefor the greater the energy received the more vigorous the water circulation and the better the system performance.

2.5.4 Collector Characteristics

The thermal performance of solar collector affected by the characteristic of its components. The main characteristics are:

2.5.4.1 Glazing Material

The optical properties of the Glazing materials have an important role in its ability for transmitting as much as solar radiation to the absorber plate and retaining it inside the collector.

The efficiency of solar collector affected by the optical properties of the glazing material. In order to attain maximum efficiency, the reflection and absorption should be as low as possible, while the transmission should be as high as possible.

Glass has been widely used to glaze solar collectors because it can transmit as much as 90 percent of the incoming shortwave solar irradiation while transmitting virtually none of the long wave radiation emitted outward by the absorber plate. Glass with low iron content has a relatively high transmittance for solar radiation (approximately 0.85–0.90 at normal incidence), but its transmittance is essentially zero for the long wave thermal radiation (5.0–50 μm) emitted by sun-heated surfaces (Kalogirou, 2014).

Plastic glazing of various types still used on some solar collectors to reduce weight and cost, but may reduce performance and lifetime. Plastics inside a well-sealed collector may deteriorate rapidly and will outgas, depositing a haze of condensed oily liquid on the inside surface of the glazing. Such haze will seriously reduce the collector efficiency (Alghoul et al, 2005).

Table 2.1: Transmittance of some glazing materials (Sadaq,et al,2015).

Material	Transmittance (τ)
Crystal glass	0.91
Window glass	0.85
Acryl ate, Plexiglass	0.84
Polycarbonate	0.84
polyester	0.84
Polyamide	0.80

Table 2.1 shows transmittances for various glazing materials when the direct solar beam is perpendicular to the glazing because the angle of the direct beam varies a somewhat lower value of τ are usually used.

2.5.4.2 Collector absorber plate

The function of the collector absorber plate is absorbing as much of the solar irradiation as possible through the collector glass cover and losing as little heat as possible upward to the atmosphere and downward through the back of the casing. Then, transfer the retained heat to the transport fluid.

The absorber plates commonly made of metals known with their high conductivity such as copper, aluminum or steel. Factors that determine the choice of absorber material are its thermal conductivity, its durability and ease of handling, its availability and cost, and the energy required to produce it (Amrutkar et al, 2012).

Normally a selective coating applied to the surface of the absorber plate to increase absorption and reduce emission from the plate, which increase the collector efficiency. Table 2.2 gives the types of selective materials and its absorptance (α) and emittance (ε).

Table 2.2: Properties of Selective Coatings (Nijaguna, B., 1992).

Selective Coatings	α	ε	α/ε
Black Chrome	0.93	0.10	9.3
Black Nickel on polished nickel	0.92	0.11	8.4
Black Nickel on galvanized iron	0.89	0.12	7.4
Cu on nickel	0.81	0.17	4.7
Co3O4 on silver	0.90	0.27	3.3
CuO on aluminum	0.93	0.11	8.5
CuO on anodized aluminum	0.85	0.11	7.7

2.5.4.3 Collector insulation

The walls of the collector are insulated to reduce thermal losses by conduction. Insulations should not be flammable, and should possess low value of thermal expansion coefficient. The most frequent insulation materials used in SWHS given in Table 2.3.

Table 2.3: Thermal conductivity of some insulation materials (Alghoul et al, 2005).

Insulating material	Thermal conductivity (W/mK) at 10 ^{o}C
Expanded polystyrene 15	0.04
Expanded polystyrene 30	0.037
Extruded polystyrene	0.27
Polyurethane foam	0.018
Phenolic foam	0.027
Cellular foam	0.41
Mineral wool	0.045

2.6 Sizing a Solar Water Heating System

Sizing the solar water heating system involves determining two major items, which are the collector area and the storage tank capacity:

2.6.1 Sizing the solar collector

In order to find the collector area, the quantity of hot water must be determined and at what temperature it is needed. This help us in finding the hot water load and then the collector area.

After determining the hot water demand for the building, the following equation is used to find collector area:

$$A_c = [m\,C_p(T_{out}-T_{in})]/\,[\eta\,I] \quad \text{..(16)}$$

Where; A_c: Collector Area, m: mass of daily water needed, C_p: specific heat capacity of water, T_{in}: Supply (mains) water temperature, and T_{out}: required hot water temperature, *I*: Average daily solar radiation on tilted surface of collector, η: collector efficiency (for FPC: 35% and for ETC: 45%).

2.6.2 Required storage tank capacity

The storage tank can be sized according to the total collector area and the daily heating load requirements. For domestic solar water heating systems in Palestine a 200 Liter storage tank is usually used with $5.1m^2$ collectors area (Ibrik and Mahmoud, 2005).

Chapter Three
Literature Review

Several studies have been performed to investigate the performance of SWHSs with different types of solar collectors and to compare between these types. These studies based on calculations, simulation programs, field tests or experiments and this chapter reviews some of these studies.

(Ayompe and Duffy, 2013) studied the thermal performance of domestic scale SWHS by experimental testing for 4 m^2 flat plate collector in a temperate climate in Dublin, Ireland, over a year. The maximum recorded collector outlet fluid temperature was 70.4 ^oC, solar fraction was 32.2%, collector efficiency 45.6% and system efficiency was 37.8% while supply pipe losses was 16.4% of energy collected.

Another Analysis study for flat plate collectors performed by (Struckmann, 2008), this study describes a way to measure the efficiency of FPC which is the most important part in SWHS by using the equation

$$\eta_c = F_R(\tau\alpha) - F_R U_L\,[(T_{in}-T_a)/G_t]$$

If it is assumed that F_R, τ, α, U_L and flow rate are constants for a given collector, then the efficiency is a linear function of the three parameters defining the operating condition: solar irradiance (G_t), fluid inlet temperature (T_{in}) and ambient temperature (T_a).

The effect of various parameters such as cold water inlet temperature, ambient temperature, insulation thickness, wind speed and transmission coefficient of the glasscover on the performance of flat plate solar collector system was studied by (Gowda et al, 2014). Experimental test was performed according to ANSI/ASHRAE on $2m^2$ FPC system in Bangalore climate conditions (clear sunny days in April), and by using "Hottel-Whiller-Bliss" equations to assess the performance of the system. The results show that the efficiency of the collector system will decrease by increasing the inlet temperature of water and by increasing wind speed. The efficiency proportionally increases with ambient temperature. The increasing in ambient temperature decreases loss of heat by radiation, convection and conduction to the surroundings. Increasing the thickness of insulation beyond 5cm is worthless as there is no effect on system efficiency. Instantaneous efficiency increases to maximum from 12 noon to 13:00 PM, it is reached 51%. Transmission coefficient of transparent covers should be more than 0.95 in order to obtain higher efficiency of the collector system.

(Shitzer et al, 1979) experimentally tested a thermosiphon solar water heating system consists of two parallel flat plate collectors with total area ($3m^2$) and one storage tank (140 Liter). The experiments were performed at the Energy Laboratory, Technion, Haifa, Israel, during 1975. The test results show relatively linear temperature distributions both along the collectors and in the storage tank and water flow rate was found to essentially follow solar radiation.

(Hayek et al, 2011) investigated the thermal performance of two types of evacuated tube solar water collectors namely, the water-in-glass tubes and the heat-pipe designs under Eastern Mediterranean climatic conditions in clear sky days in the period between November and January, results showed that the heat-pipe-based collectors are higher efficiency of 15%-20% than the water-in-glass designs. A similar experimental investigation was performed by (Mishra, 2015) but the comparison was between evacuated U-tube collector and water-in-glass evacuated tube collector, the results show that the U-tube technology is much efficient around 10% to 15% than water-in-glass.

(Sabiha et al, 2015) published an article about the progress and latest developments of evacuated tube solar collectors. Their article shows that an evacuated tube collector has higher efficiency than the other types of collectors. ETC is highly recommended for higher temperature applications as they can gain higher temperatures easily and are able to preserve heat even when the outside weather is cold.

They clarify the challenges that needed to be addressed before installing an evacuated tube solar collector. The article gives also recommendations to overcome the barriers and to enhance performance of an evacuated tube solar collector.

(Morrison et al, 2004) studied in their research the performance of a water-in-glass evacuated tube solar heater using the international standard test method ISO 9459-2. The study shows that Water-in-glass evacuated tube solar water heaters operate effectively in a range of climatic conditions, but the numerical simulations have shown the existence of inactive region in the bottom of the tube that would influence the performance of the collector.

(Kasaeian et al, 2014) used TRNSYS software to simulate the evacuated tube solar water heating system with natural circulation under the climatic conditions in Tehran, Iran. The type used is water-in-glass ETC which is widely used in the world. Results showed that the heat loss in summer become less than the winter season. The instantaneous efficiency and outlet temperature of the collector in warm months is greater than cold months. A similar study prepared by (Azimi et al, 2016) with the same results, but they used some variables such as the diameter of inner tube, length of tube, velocity of natural circulation between the tubes and tilt-angle of the collector to optimize the performance of ETC in Iran Using TRNSYS software.

(Ayompe and Duffy, 2013) performed a thermal performance analysis on Solar water heating system with Heat Pipe ETC using data from a field trial over a year in Dublin, Ireland. The maximum recorded collector outlet fluid temperature was 70.3 ^{o}C, solar fraction was 33.8%, collector efficiency was 63.2%, system efficiency was 52.0%, and supply pipe losses was 17.7% of energy collected.

(Bisla and Mor, 2017) studied the effect of adding flat and parabolic reflectors to the ETC on different parameter such as efficiency, energy and exergy. The experiment take place in Hisar, India. The experimental analysis shows that the ETC tube with flat reflector has more efficiency than without any reflector. And ETC with parabolic reflector has more efficiency than with flat reflector.

(Almasri and Almarshoud, 2017) performed a feasibility study for using evacuated tube solar water heaters in six locations of different climatic in Saudi Arabia using RET Screen program. The study showed the feasibility of using evacuated tube solar water heating system with heat pipe in Saudi Arabia, especially that the resulting payback time is between 3.4- 3.9 years for the investigated locations.

(Ayompe et al, 2011) conducted a field study to compare the performance of 4 m^2 flat plate and 3 m^2 heat pipe evacuated tube collectors for domestic water heating system in Dublin, Ireland. Under the same weather conditions, the collector efficiencies were found to be 46.1% and 60.7% and the system efficiencies were 37.9% and 50.3% for Flat plate collector and heat pipe evacuated tube collector, respectively.

In a research for (Nájera-Trejo et al, 2016) to determine the economic feasibility of using flat plate versus evacuated tube solar collectors for domestic hot water and radiant floor heating (combisystem) for a building in Chihuahua, Mexico, the TRNSYS software was used for design and thermal analysis, while Microsoft Excel was used for techno-economic analysis. The optimum system configuration in case of evacuated tube was 8 collectors using a storage relation of 40 L/m^2, whereas for flat plate was 12 collectors using a storage relation of 50 L/m^2. The return on investment for the flat plate system was calculated in 9 years and the evacuated tube system resulted in approximately 11 years.

(Zambolin and Del Col, 2010) presented experimental analysis for the thermal performance of flat plate and evacuated tube solar collectors in their paper. Their aim was to compare the daily energy performance of these two types of collectors. Comparative tests were performed by installing the two types of collectors in parallel on the terrace roof of the University of Padova and tested at the same working conditions using steady-state and quasi-dynamic methods. The results show an agreement between SST and QDT for each collector. The daily energy collected has a linear relationship with the daily solar radiation energy, at constant operating temperature difference.

The flat plate collector is more sensitive to the temperature difference than the evacuated tube collector. The evacuated collector displays a higher efficiency for a larger range of operating conditions, as compared to the flat plate collector.

(Yasin, 2017) evaluated the performance of glazed and evacuated tubes solar collectors technically and financially using RETScreen software. The study performed over Palestinian territories (West Bank & Gaza) which divided into five topography regions. By simulation, the optimal tilt angle of the solar collectors in all sites is found to be the latitude of each site or latitude plus 15^o. The payback period for all regions is in range of 2 and 2.5 years for flat plat collectors and evacuated tube collectors. The performance of SWH systems is mostly similar all over Palestinian territories whether glazed or evacuated tubes are used.

(Hernández and Guzmán, 2016) made a comparison between three water heating systems; two flat plate collectors (one with copper coil, the other with stainless steel coil) and one vacuum tube heater, all of them are on top of the “Universidad Pontificia Bolivariana” in Bucaramanga, Colombia. Testing results show that the maximum efficiency is 71.58% for stainless steel coil collector, 76.31%for Copper coil collector and 72.33% for the vacuum tube heater collector. While the vacuum tube heater collector was the most efficient along with the weather conditions at the time of the testing.

(Yasin et al, 2011) used the SWHS of main cafeteria in Birzeit University-Palestine which consists of 148 m^2 of solar collectors and 3000 Liter storage tank as a case study to determine the utilized energy and CO_2 saving. The utilized heat energy from SWHS in 10 days, measurements period, is 1158 kWh and the corresponding savings in CO2 emissions are 585 and 1163 kg in case of using diesel and electric boilers, respectively.

(Wang, et al, 2018) studied the effect of solar radiation and weather conditions on the performance of solar water heater. They find that the influence of the weather on the solar irradiance is large, and the irradiance has a great influence on the water temperature.

(Akanmu and Bajere, 2015) presented in their study a detailed experimental observations of temperature, solar radiations, and mass flow rate for thermosiphon solar water heating system with four flat plate collectors, connected in series. They noted that an average of 65.5 ^{o}C water temperatures is obtained daily with high temperatures reaching 90 ^{o}C on excessive hot days of March to May annually. Water temperatures in the hot water tank are of the range 45 ^{o}C to 78 ^{o}C and a mass flow rate averaging 55kg/hr was achieved for the system.

(Morrison et al, 2004) discussed the factors influencing the natural circulation rate through the water-in-glass evacuated tubes collector and presented the numerical study of water circulation through long single-ended thermosiphon tubes.

(Tambunan et al, 2018) studied the effects of absorptivity and transmissivity of the glass cover on performance of flat plate solar collector numerically and validated the numerical results experimentally.

(Shariah et al, 2002) used the indictor of annual solar fraction to find the optimum inclination angles for a thermosiphon solar water heater in northern and southern parts of Jordan. Calculations were carried out using program TRNSYS. They found that the optimum inclination angle for the maximum solar fraction is about $\phi+(0\rightarrow^{o}10)$ for the northern region and about $\phi+(0\rightarrow^{o}20)$ for the southern region, where ϕ is the location latitude.

(Bhamare et al, 2018) proposed analytical model to study the performance of a thermosiphon solar water heating system. This proposed model predicts the temperature and mass flow rate in a thermosiphon solar water heating system depending on radiation intensity and ambient temperature.

(Koffi et al, 2008) conducted a theoretical and experimental analysis of the thermal performance of a thermosiphon solar water heater prototype with an internal exchanger. Measurements of the total irradiation received by the collector, total daily irradiation, temperatures in various points of the system and the storage tank, etc., are reported in order to determine the mass flow rate and the thermal performances of this system. They observed qualitative and quantitative agreement between the experimental and theoretical results of mass flow rate and temperatures. The collector outlet water temperature levels were more than 85.5 ^{o}C and a collector efficiency around 58%.

(Esen, M., Esen, H., 2005) investigated a two phase closed thermosiphon for different refrigerants like R134a, R410A, R407C. They observed that maximum collector efficiency of 50.84% is obtained for systems using refrigerant R410A as a working fluid.

The literature review shows that there is a limited study of the thermosiphon solar water heating systems in West Bank, Palestine. In addition, the few experimental studies that were performed didn't compare between the thermal efficiency of different solar collector systems.

This study was undertaken to investigate the thermal performance of thermosiphon solar water heating system which consists of evacuated tube collector, parallel type flat plate collector and serpentine type flat plate collector under the weather of West Bank and to find the efficiency of each collector system and then to make a comparison between them.

Chapter Four
Research Methodology

4.1. Research Methodology

The main activities that have been followed to achieve the goals of this research are:

4.1.1 Field experiment

The thermal performance of the different types of solar water heating collectors has been analyzed and compared using data obtained from a field experiment executed on rooftop of Energy Research Center building at An-Najah National University-Nablus, Palestine.

4.1.1.1 Experimental procedure

Three prototypes of solar water heating systems, two with flat plate collector and one with evacuated tube collector are installed side by side on the rooftop of Energy Research Center building at Al-Najah National University, in Nablus (32.227099N, 35.222209E), Palestine.

The experiments were conducted in specific days during May and June 2019. Throughout the testing period, the collectors faced south at fixed tilt angle 32 degree. A measurement for global irradiation on collector plane, collector's inlet temperature, collector's outlet temperature, storage tank temperature and surrounding air temperature were acquired every 15 minutes from 9:00 AM until 1:45 PM.

4.1.1.2 Experiment design

The layout of the comparative experimental prototype for flat plat and evacuated tube collectors is shown in Figure 4.1.

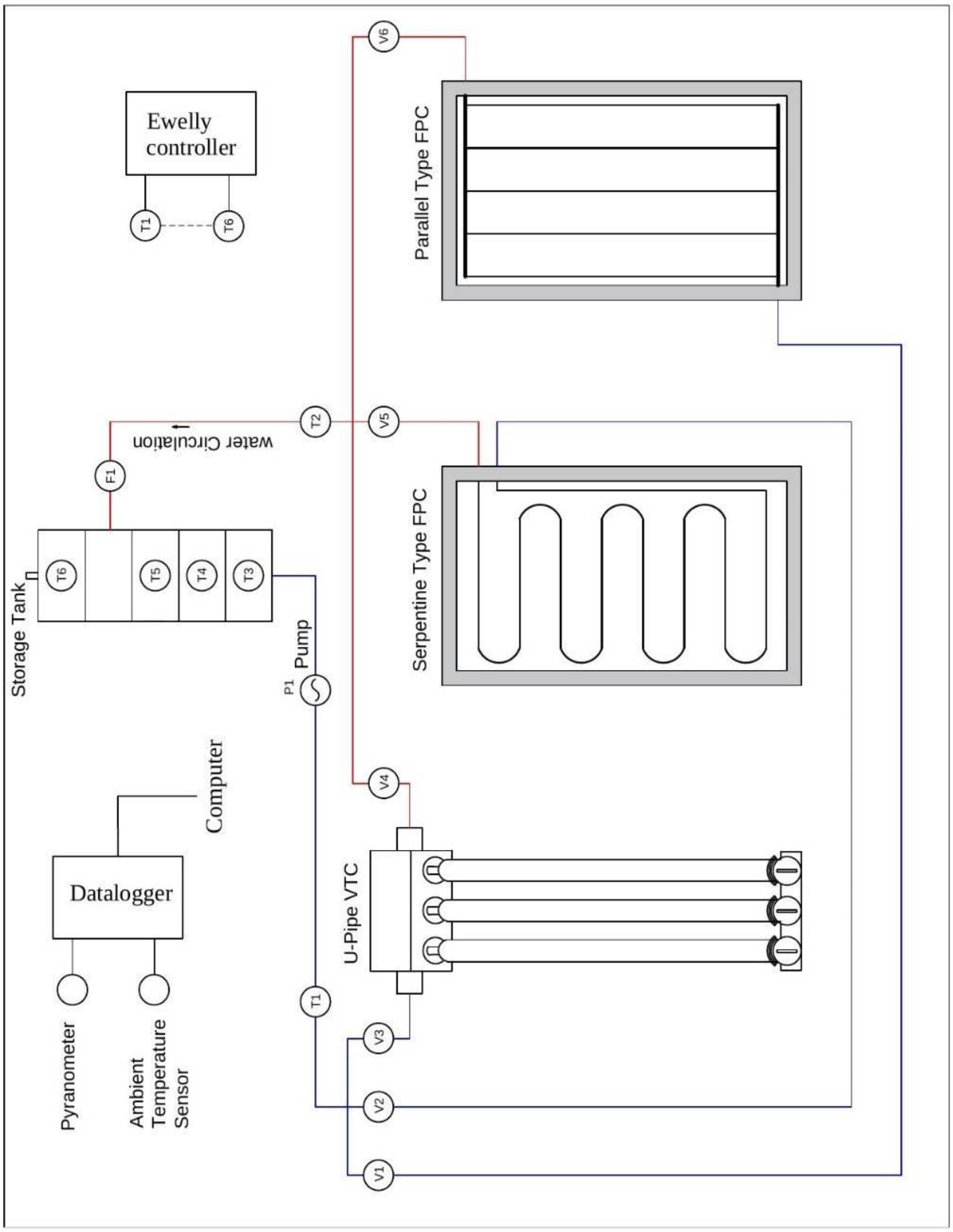

Figure 4.1: Layout of experimental prototype.

The experimental set-up consists mainly of 0.48 m^2 Parallel type FPC(P-FPC), 0.48 m^2 Serpentine type FPC(S-FPC), 0.31 m^2 U-Pipe ETC and one cylindrical tank with 30 Liter storage capacity.

The design of the experimental model was in a way that the comparison systems shared all parts except the collectors in order to keep the structure parameters consistent.

The two flat plate and the evacuated tube collectors were in parallel, and water was circulated between the collectors and the storage tank.

Control Valves were used to control the water flow between collectors, such that one collector can be tested at a time. When the control valves V2, V3, V4, V5 were closed and V1 and V6 were opened, the P-FPC was operated; when the control valves V1, V3, V4, V6 were closed and V2 and V5 were opened, S-FPC was operated. Finally, when the control valves V1, V2, V5, V6 were closed and V3 and V4 were opened the ETC was operated.

Figure 4.1 shows also the position of the thermocouple sensors. These sensors were used to measure water temperature at the collectors inlet (T1), water temperature at the collector outlet (T2), water temperature at the bottom of the water tank (T3), water temperature at the middle of the water tank (T4 and T5) and the water temperature at the top of the water tank (T6).

The global solar radiation incident on the collector surface and the surrounding air temperature were measured by Meteocontrol weather station, connected to a datalogger, which records the data every 15 minutes.

The experiments were conducted on days 22, 26, 27, 28, 29, 30 of May 2019, and 17, 25, 26, 10, 24, 20, 23 of June 2019.

4.1.1.3 Experiment instrumentation

The experimental set up appears in Figure 4.2, it consists of the following items:

Figure 4.2: Experimental set up

1- S-FPC

A rectangular flat plate collector with 1.0 m long and 0.6 m wide has been used in the experiment. The collector box is made of powder-coated aluminum of 2 mm layer thickness and covered by transparent glass with 4mm thickness. Internally, it is covered by a thermal insulating sheet (Rockwool) of 3 cm thickness. A layer of steel sheet 1 mm thickness painted with selective coating was used as the absorber plate. The internal pipes made of copper with diameter 3/8" and total length 5.5 m, arranged in serpentine back model. The effective area of the S-FPC is 0.48 m^2.

2- P-FPC

The solar collector box is made of 2 mm thickness aluminum sheets. Its dimensions are 1 m long and 0.6 m wide, with a total area of 0.6 m^2 and effective area of 0.48 m^2. Inside the box, a five parallel copper pipes, 1/2" diameter each, are connecting at the bottom and top with 1" copper headers. The copper tubes lay on 3 cm Rockwool and covered by mm steel sheet with selective coating. 4 mm thickness transparent glass has been used to cover the collector box.

3- **U-Pipe ETC**

The evacuated tube collector is U-pipe type composed of three tubular glasses. Each evacuated tube has 1.8 m length and 58 mm outer diameter with total effective area 0.31 m^2. The copper pipes inside the evacuated tubes have 9.4 m length and 3/8" diameter.

4- Water tank

Vertical storage water tank was used in the experiment. Its length 65 cm and diameter 25 cm, with total capacity 30 Liter. The tank is well insulated by Rockwood.

The tank has two openings at the Top, one for filling the tank with water, and the other is hot water inlet from collector (inlet of the tank). And has one opening at the bottom for cold water outlet for supplying the collector (outlet of the tank).

5- Connection pipes

16 mm^2 PVC pipes were used to connect the solar collectors with the storage tank.

6- Temperature sensors

Six temperature sensors were used in the experiment. Four of them were inserted inside the tank at different levels to measure the tank temperature. One is to measure the collector outlet temperature and the last one is to measure the collector inlet temperature.

Sensors are K-Type thermocouple with measuring temperature range (-270° C to 1260° C) and accuracy +/-2.2° C.

Temperature readings are collected and showed using Ewelly controller (EW-181)

7- Weather station

Meteocontrol weather station was used to measure the ambient temperature and the global solar radiation at the tilted collector surface. The data were collected and stored every 15 minutes by datalogger.

4.1.2 Energy analysis

The collected data from field experiments were used to evaluate the energy performance indices, which are the received energy, energy delivered and system efficiency.

1- Received energy

If G_t is the intensity of solar radiation, in W/m^2, incident on the tilted plane of the solar collector having a collector surface area of A_c, in m^2, then the amount of energy received by the collector is:

$$Q_{in} = Ac\int_{t1}^{t2} Gt\, dt$$

2- Energy delivered

The useful thermal energy that has been collected by the solar water heating system is given equation (15):

$$Q_u = m\, C_p \frac{d\bar{T}}{dt}$$

3- System efficiency

The overall system thermal efficiency η_{sys} is calculated by equation (14):

$$\eta_{sys} = (\int_{t1}^{t2} Qu\ dt)/(Ac\int_{t1}^{t2} Gt\ dt)$$

4.1.3 Economical analysis

Installation of SWH system reduces the operational costs due to the energy consumption.

Simple payback period (SPP) and Net present value (NPV) were used to evaluate the economic feasibility of using each type of the three SWH systems. Therefore, the feasibility of each system is analyzed considering the equipment cost, operation cost and system life span.

The SPP is a common and easy way to evaluate the economic value of a project. It is the number of years required to return the initial investment. The simple payback period is the project fixed cost (C_0) to the annual saving (S), it is given by:

$SPP = C_0/S$……………………………………………………………(17)

The total life cycle cost is the total of the fixed cost (C_0) and running cost ($C_{running}$):

$C = C_0 + C_{running}$…………………………………………………………(18)

Fixed cost is the initial cost of system or materials cost and the running cost is the operational and maintenance cost during the life span of the system.

The annual revenues (R) are the averaged energy cost avoided annually, which consists of the annual energy savings (Es) multiplied by the cost per energy unit (Ayompe et al, 2011).

The quantity of conventional energy displaced annually (Es) is computed as:

$E_S = Q_u / \eta_{boiler}$……………………………………..……………………..…(19)

Where, η_{boiler} is the electric heater efficiency (boiler) and Q_u is the useful energy collected by the solar water heating system.

The annual revenues is computed as:

$R = Es * E_{tariff}$………………………………………………………………….….(20)

The total revenue (R_t) accrued over the service life of the SWHS is given as:

$R_t = \sum_{1}^{20} R$, system life span is 20 years**……………………………….(21)**

NPV is the difference between the total revenues (R_t) and the total cost (C) during system life cycle.

$NPV = R_t - C$…………………………………………………….……………….(22)

Chapter Five

Results and discussions

5.1 Solar radiation and ambient temperature

1- S-FPC

The recorded data for solar radiation and ambient temperature, during test period of S-FPC heating system are shown in Figure 5.1.

During the four test days, the weather was sunny with clear sky, and the result was a smooth solar radiation curves.

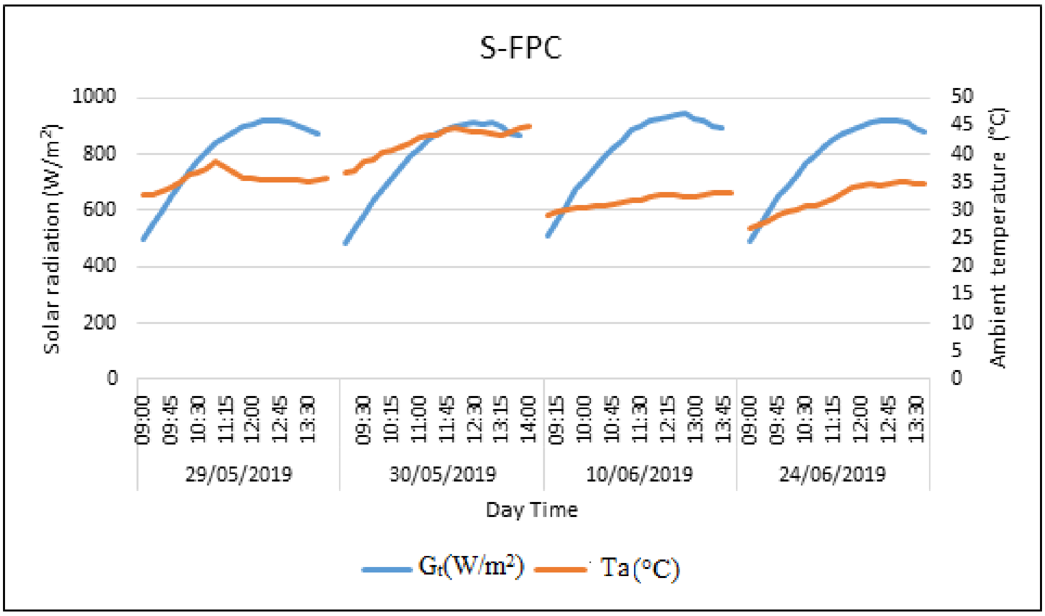

Figure 5.1: Weather data for S-FPC test days

Table 5.1 show the summery of average solar radiation and ambient temperature during the test period for all test days for the S-FPC.

Table 5.1: Summery of weather data for test days of S-FPC.

Collector type	Date	$G_{t.avg}$ (W/m^2)	$T_{a.avg}$(°C)
S- FPC	29/05/19	801.8	35.5
	30/05/19	788.8	42.2
	10/06/19	818.2	31.6
	24/06/19	796.1	32.1

2- P-FPC

Figure 5.2 shows the data collected during the test days (22/05/19, 28/05/19, 17/06/19, 25/06/2019, 26/06/2019) of P-FPC heating system. All the days were sunny except 17/06/19.

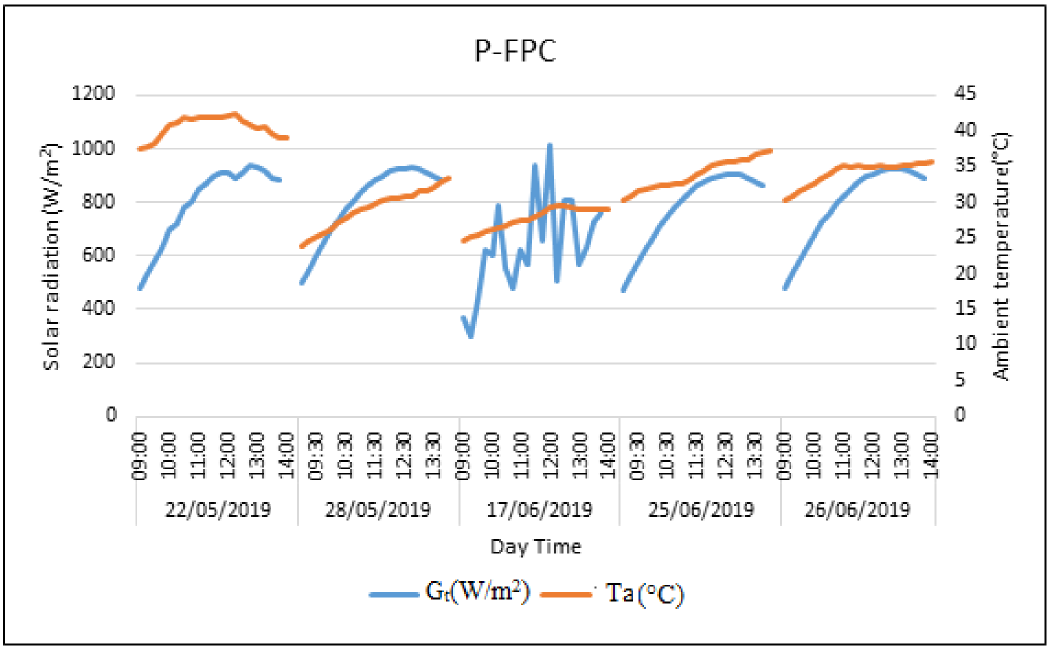

Figure 5.2: Weather data for P-FPC test days

Table 5.2 show the summery of average solar radiation and ambient temperature during the test period for all test days for the P-FPC.

Table 5.2: Summery of weather data for test days of P-FPC.

Collector type	Date	$G_{t.avg}$ (W/m^2)	$T_{a.avg}$(°C)
P-FPC	22/05/19	800.9	40.3
	28/05/19	804.2	29.1
	17/06/19	637.5	27.6
	25/06/19	780.9	33.9
	26/06/19	796.2	33.9

3- ETC

Figure 5.3 show the solar radiation and the ambient temperature for the test days of ETC.

All days were cloudy except 23/06/19, which was sunny day.

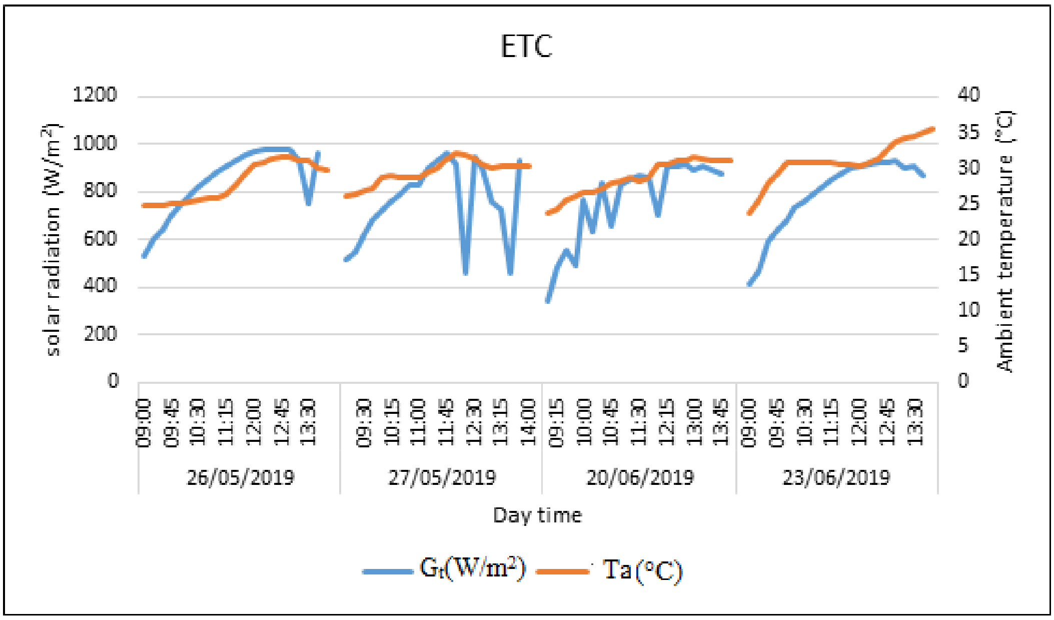

Figure 5.3: Weather data for ETC test days

Table 5.2 show the summery of average solar radiation and ambient temperature during the test period for all test days for the ETC.

Table 5.3: Summery of weather data for test days of ETC.

Collector type	Date	$G_{t.avg}$ (W/m^2)	$T_{a.avg}$(°C)
ETC	26/05/19	844.2	27.9
	27/05/19	760.9	29.4
	20/06/19	759.7	28.6
	23/06/19	791.9	30.8

5.2 System temperatures:

1- S-FPC

Figure 5.4 is a plot for the inlet and outlet temperatures of S-FPC and the average tank temperature, which were recorded every 15 minutes.

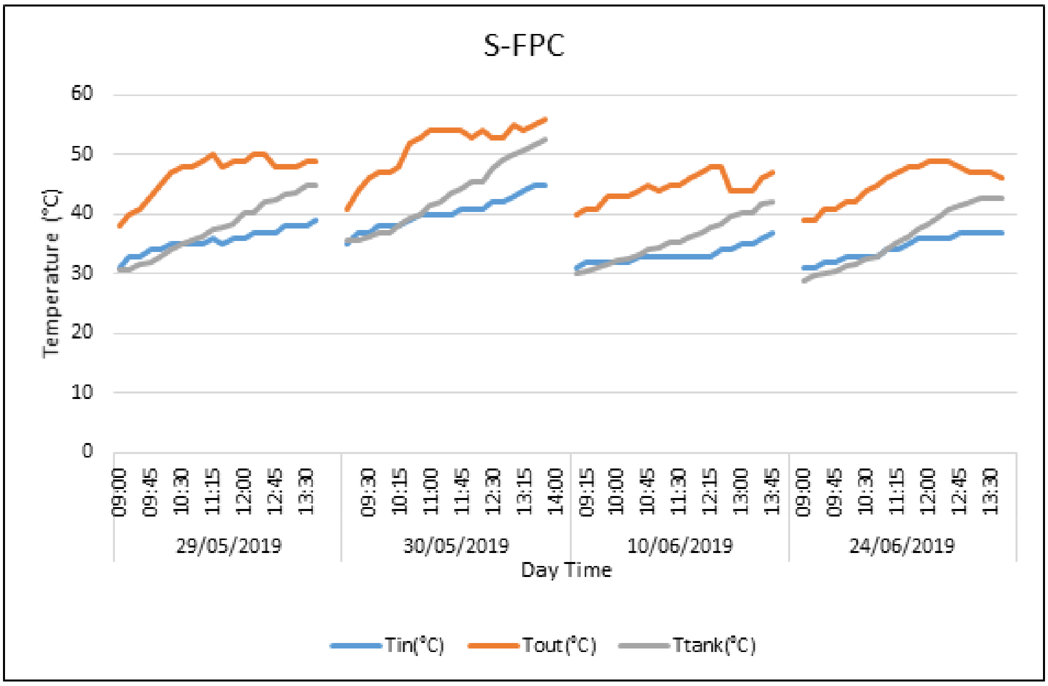

Figure 5.4: S-FPC system temperatures

The system temperatures are gradually increasing as the solar radiation and ambient temperature are increasing.

The hottest test day (30/05/19) achieved the highest values for T_{out} and $\overline{T}_{tank}$, which were 56° C and 52.5° C respectively. While 10/06/19 the day of min ambient temperature achieved the lowest value for T_{out} , which was measured 48° C and the lowest value for $\overline{T}_{tank}$ which was 42.25° C.

2- P-FPC

The parallel type FPC was tested in five days of different weather condition.

The highest value for $\overline{T}_{tank}$ was 53.25° C recorded in 22/05/19 the day of the highest ambient temperature and solar radiation, and the lower was in 17/06/19 with 38.75° C. 25-26/6/19 the days with the same weather conditions achieved the same $\overline{T}_{tank}$, which was 48.25° C, and 48.75° C respectively.

The max T_{out} was between 44° C and 55° C and the min T_{in} was between 24° C and 38° C for the five days.

The average tank temperature and collector input-output temperature curves appear in Figure 5.5. T_{in}, T_{out} and $\overline{T}_{tank}$ are increasing up to 13:00 pm then start in decreasing because of the behavior of solar radiation and the ambient temperature.

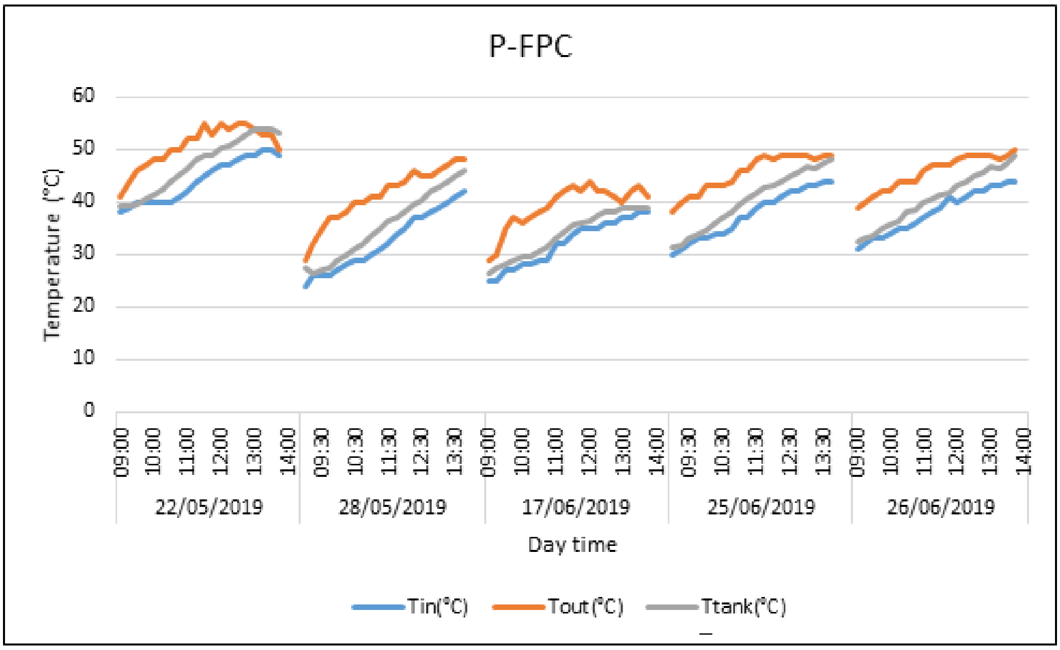

Figure 5.5: P-FPC system temperatures

3- ETC

The highest value for $\overline{T}_{tank}$ attained from the ETC was 45° C in 23/06/19 and the lowest is 41.5° C, which was in 20/06/19.

The maximum value for output temperature is 65° C which was in 26/05/19, and the lower was 46° C in 20/06/19.

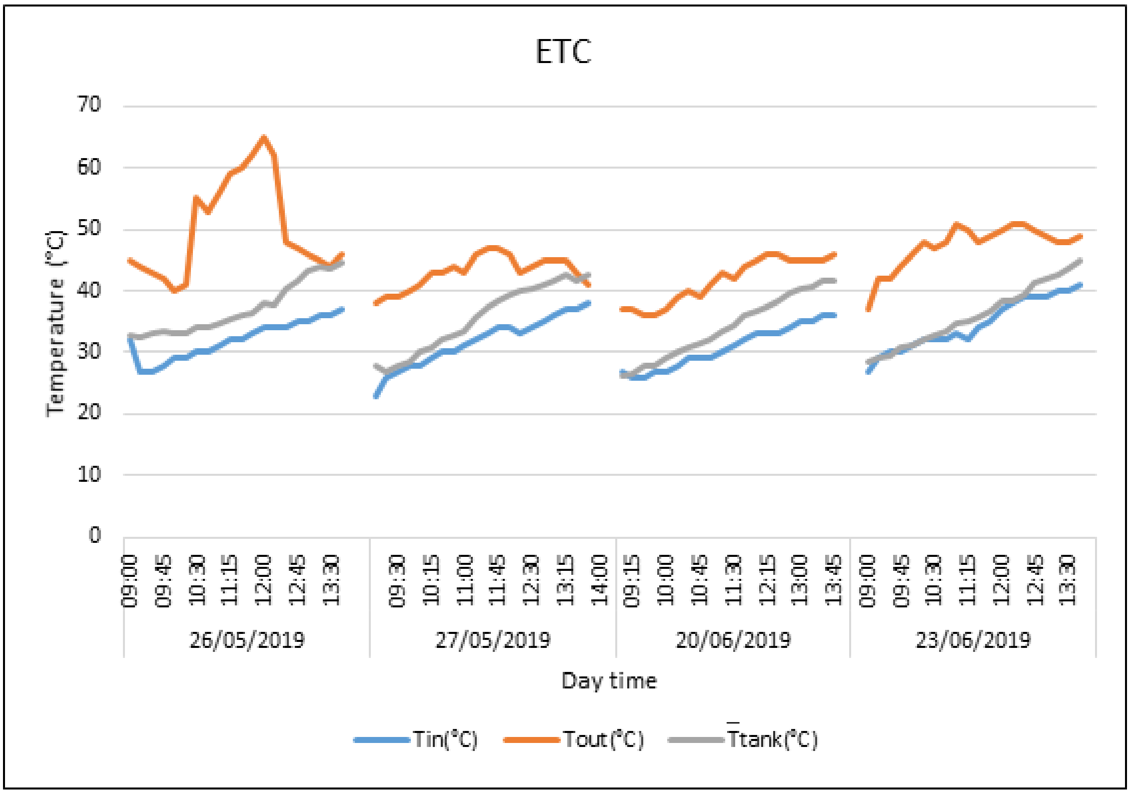

Figure 5.6: ETC system temperatures

The behavior of the ETC system in 26/05/19 is different from other days as appears in Figure 5.6 this was because the three collector was operating at the same up to 8:45 Am then the S-FPC and P-FPC were turned off.

5.3 Collected energy

1- S-FPC

Figure 5.7 shows the energy collected per m^2 by the S-FPC system at 0.25-hour intervals. The total energy collected for period (9:00 AM-1:45 PM) was 1016 Wh/m^2 in 29/05/19 and 24/06/19, 1216 Wh/m^2 in 30/05/19 and

889 Wh/m^2 in 10/06/19. All test days of S-FPC nearly have the same average solar radiation but they are different in the ambient temperature. The highest energy were collected in 30/5/19 the day of highest ambient temperature while the minimum energy was collected in 10/6/2019 the day of minimum ambient temperature.

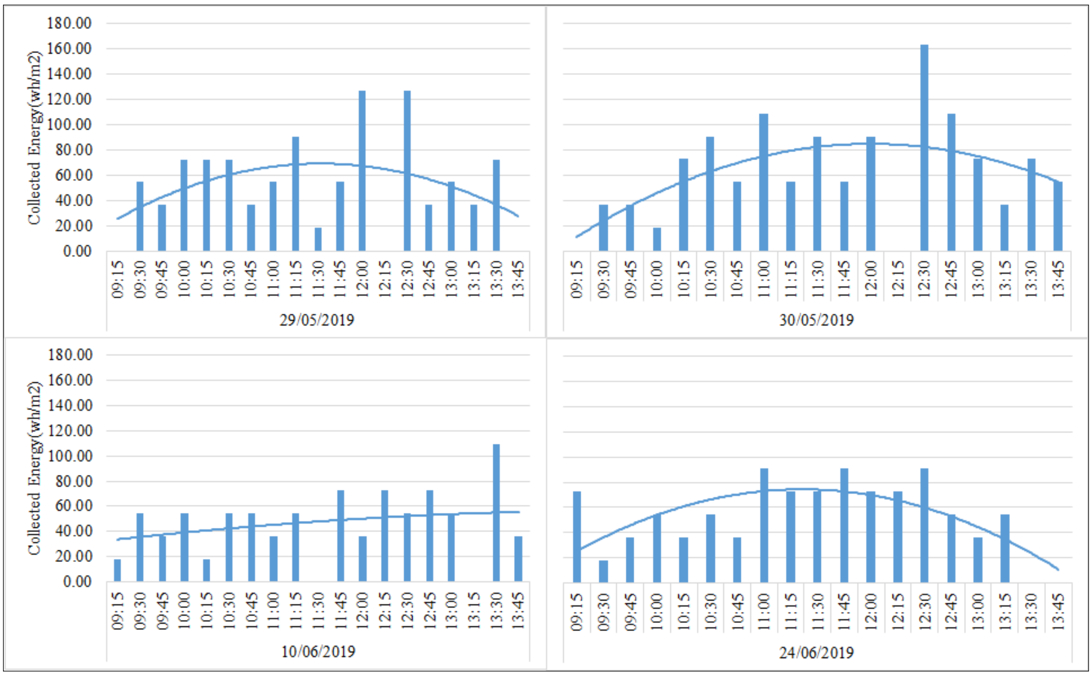

Figure 5.7: Energy Collected by S-FPC for 0.25 hour intervals

The trend line in Figure 5.7 shows the behavior of the S-FPC during the day, the collected energy starts in increasing as the solar radiation increases then start in decreasing as the solar radiation decreases also.

Figure 5.8 shows a scattered plot of the hourly energy collected against hourly solar energy input.

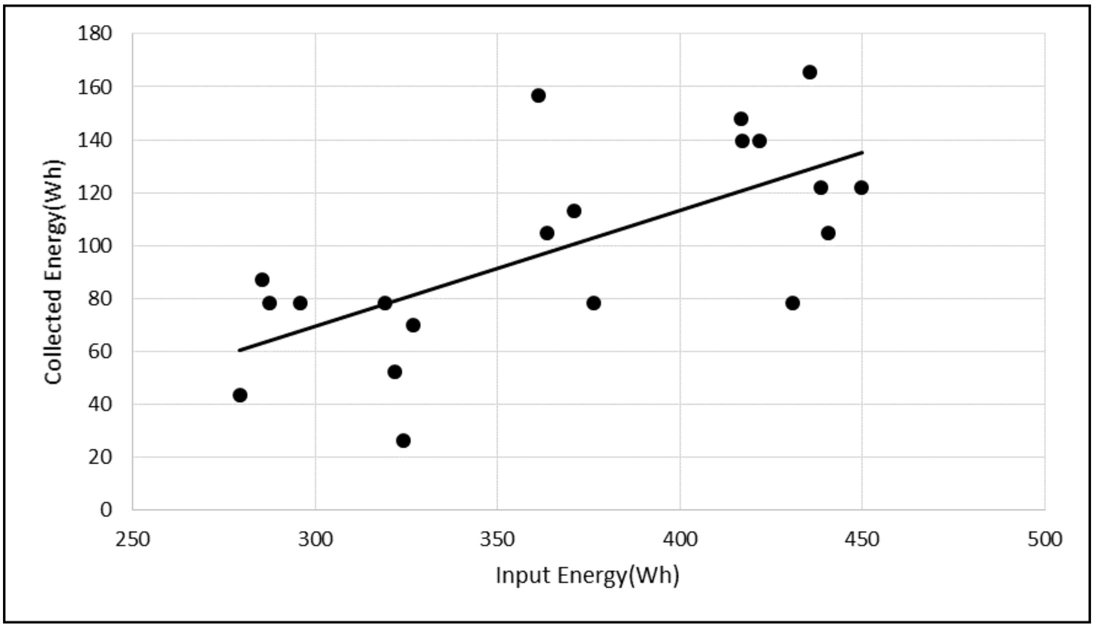

Figure 5.8: Experimental points in input–output diagram for S-FPC

It is seen that the hourly energy collected by the S-FPC has a linear relationship with hourly solar energy input, so the hourly energy collected by the S-FPC can be predicted for any given hour known total hourly solar energy using equation:

$$y = 0.4381x - 62.009$$

$$R^2 = 0.45$$

2- P-FPC

Figure 5.9 shows the energy collected diagram for P-FPC for 0.25 hour intervals for test days 22/05/19, 28/05/19, 17/06/19, 25/06/19 where the total energy collected during the test period for these days was 1016 Wh/m^2, 1415 Wh/m^2, 761 Wh/m^2 and 1216 Wh/m^2 respectively.

The lowest daily energy collected was in the cloudy day (17/06/19) the day of min solar radiation.

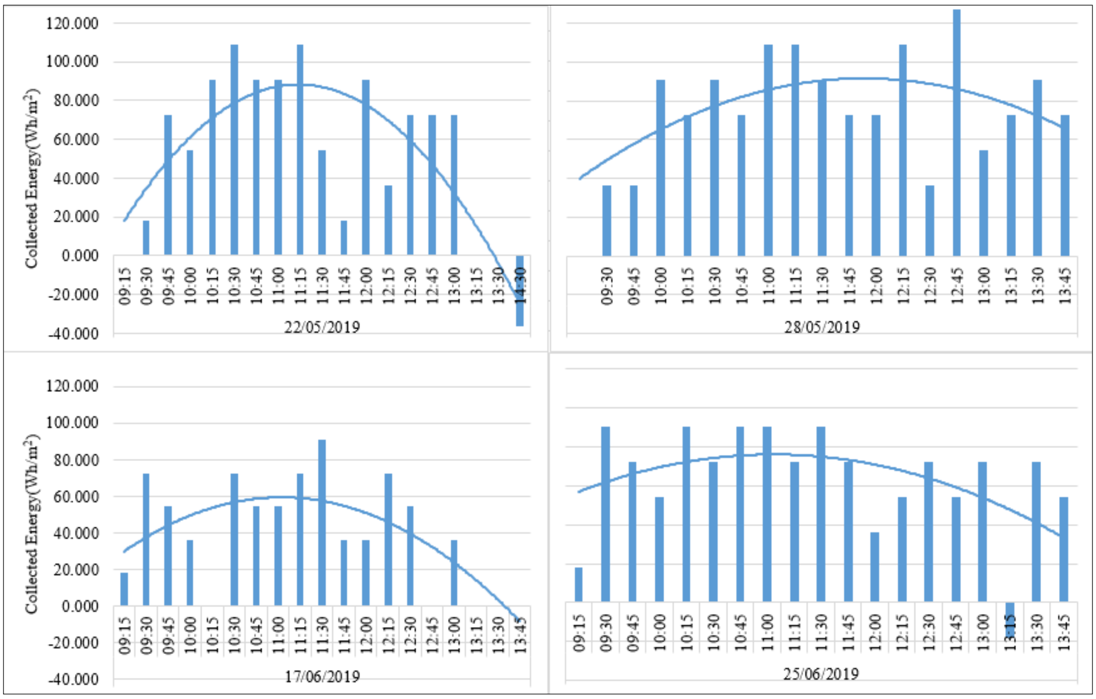

Figure 5.9: Energy Collected by P-FPC for 0.25 hour intervals

The relation between input and output energies collected by P-FPC appears in Figure 5.10, this linear relation can be expressed by equation:

$y = 0.4431x - 49.61 \; R^2 = 0.34$

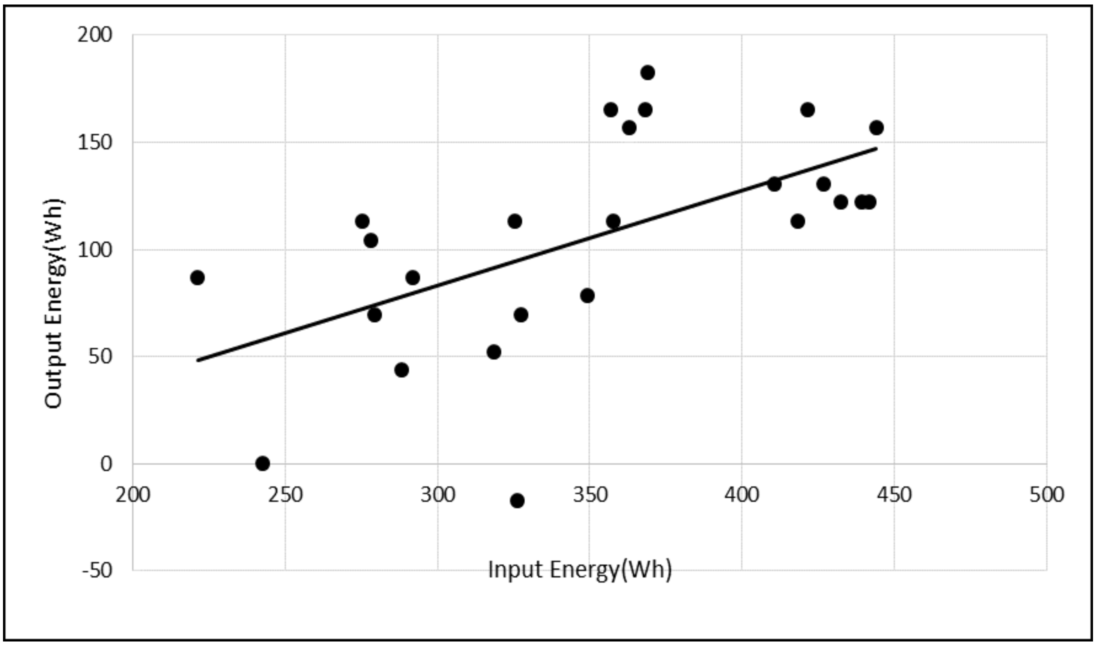

Figure 5.10: Experimental points in input–output diagram for P-FPC

3- ETC

As the S-FPC and P-FPC, the energy collected by ETC in periods of 0.25 hour was blotted in Figure 5.11. The appearance of negative energy balance in 26-27/05/19 at the beginning and the end of the day was explained by (Ayompe et al.2011), such that the ETC system tends to operate during low levels of solar insolation at sunrise and sunset. This has an impact on the quantity of energy collected since short intermittent flows of the water tends to carry heat away from the hot water tank and dump it into the collector leading to energy losses.

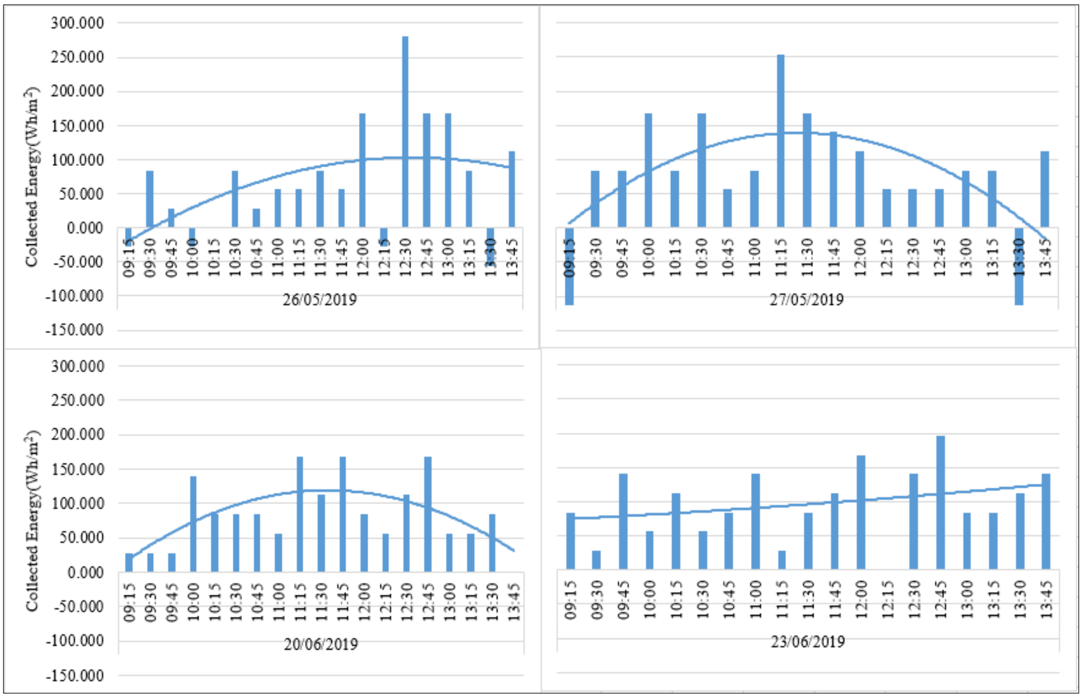

Figure 5.11: Energy Collected by ETC for 0.25 Hour intervals.

The total energy collected in 26/05/19 was 1320 Wh/m^2, 1629 Wh/m^2 in 27/05/19, 1601 Wh/m^2 in 20/05/19 and finally, 1854 Wh/m^2 in 23/6/2019.

The plot of hourly input-output energy for ETC was appears in Figure 5.12, the data scattering for ETC is less than P-FPC and S-FPC.

The Linear equation that related the output energy to input energy can be expressed by: $y = 0.7829x - 81.299$, $R^2 = 0.45$

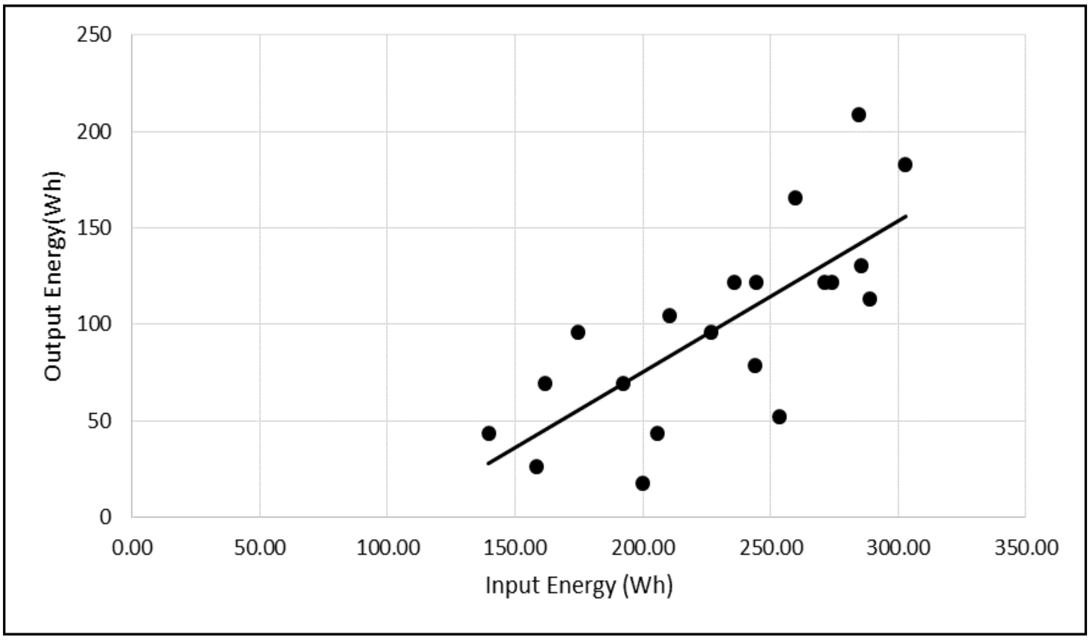

Figure 5.12: Experimental points in input–output diagram for ETC

5.4 System efficiency:

1- S- FPC

Figure 5.13 plots of the average hourly global in-plane solar radiation, S-FPC hourly efficiency on the 29/05/19, 30/05/19, 10/06/19 and 24/06/19, and Figure 5.14 plots the ambient temperature, S-FPC efficiency for the same days.

The respective minimum and maximum hourly efficiencies of the S-FPC was 44% and 8%. The average efficiency was 26% in 29/05/19, 31% in 30/05/19, 23% in 10/06/19 and 27% in 24/06/19.

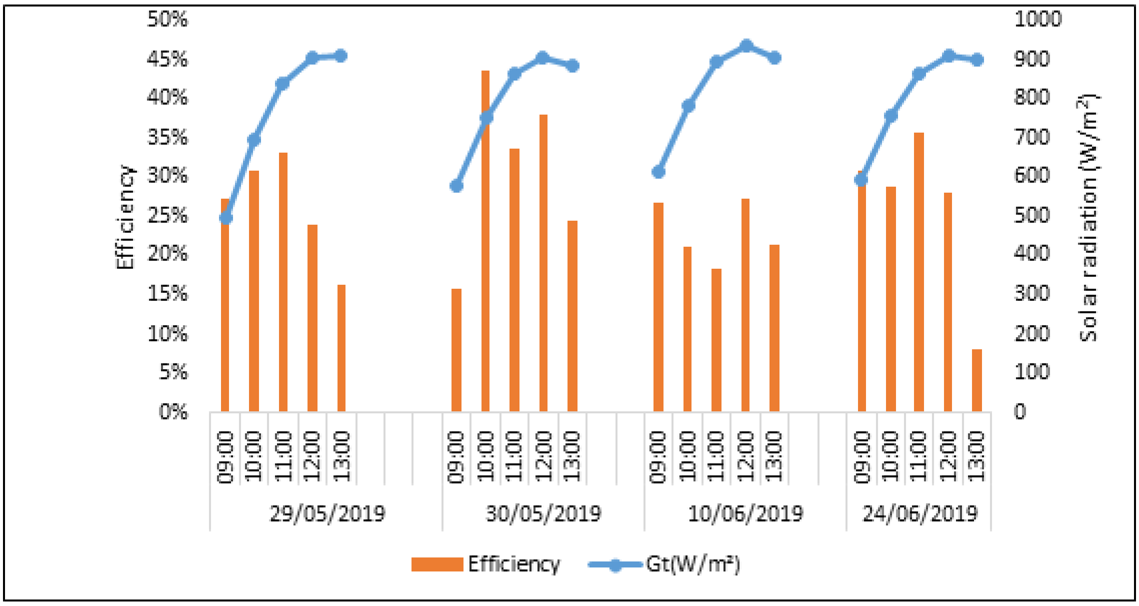

Figure 5.13: Hourly global in-plane solar radiation, S-FPC efficiency

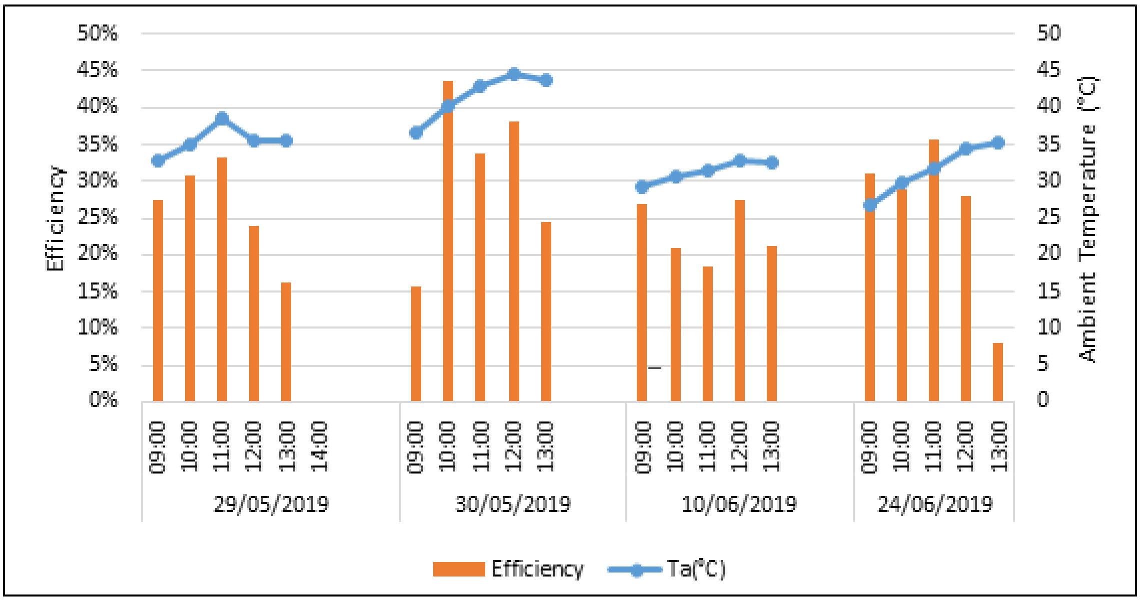

Figure 5.14: Ambient temperature, S-FPC efficiency

Figure5.13 and Figure 5.14 clearly show the direct relation between the hourly effeciency, incident solar radation and ambient temperature.

The highest efficiency was in the day of highest ambient temperature while the total incident solar radiation was nearly the same for all days.

2- P-FPC

The average efficiency of the P-FPC was 29%, 38%, 27%, 36%, and 34% in 22/05/19, 28/05/19, 17/06/2019, 25/6/19 and 26/06/19 respectively.

Figure 5.15 and Figure 5.16 shows the realation between the daily effeciency , ambient temperature and the in plane solar radiation. The day of the minimum effeciency is 17/06/19 which has the minimum solar radiation and minimum ambient temperature.

The maximum hourly effeciency achieved by the flat plate collector is 48% and the minimum was 16%.

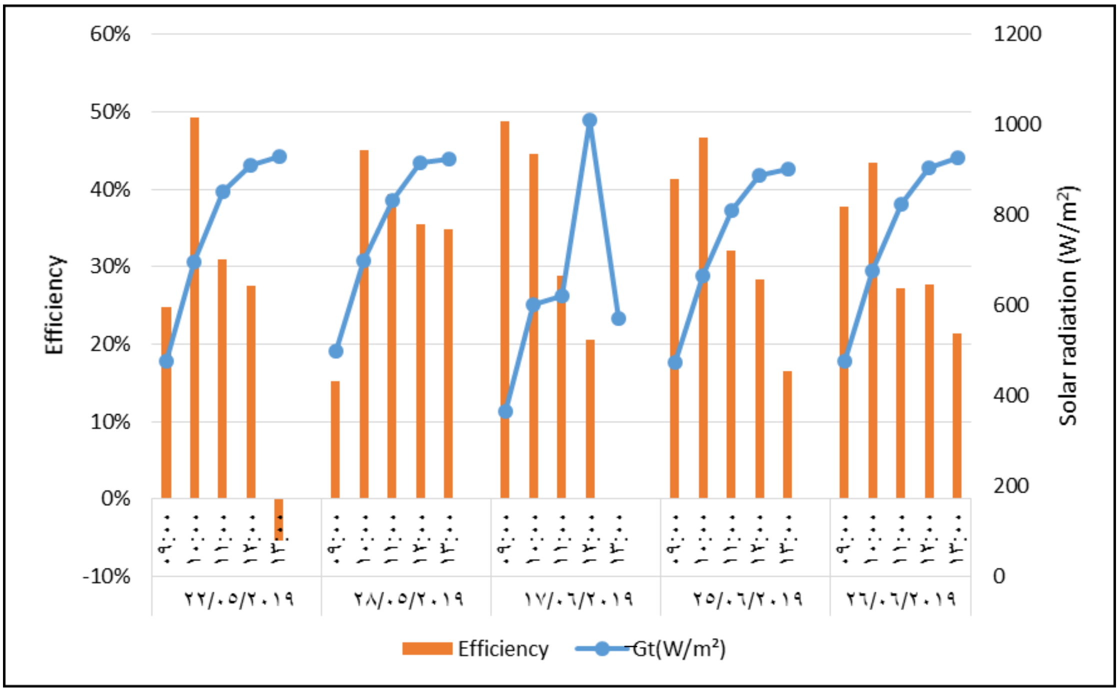

Figure 5.15: Hourly global in-plane solar radiation, P-FPC efficiency

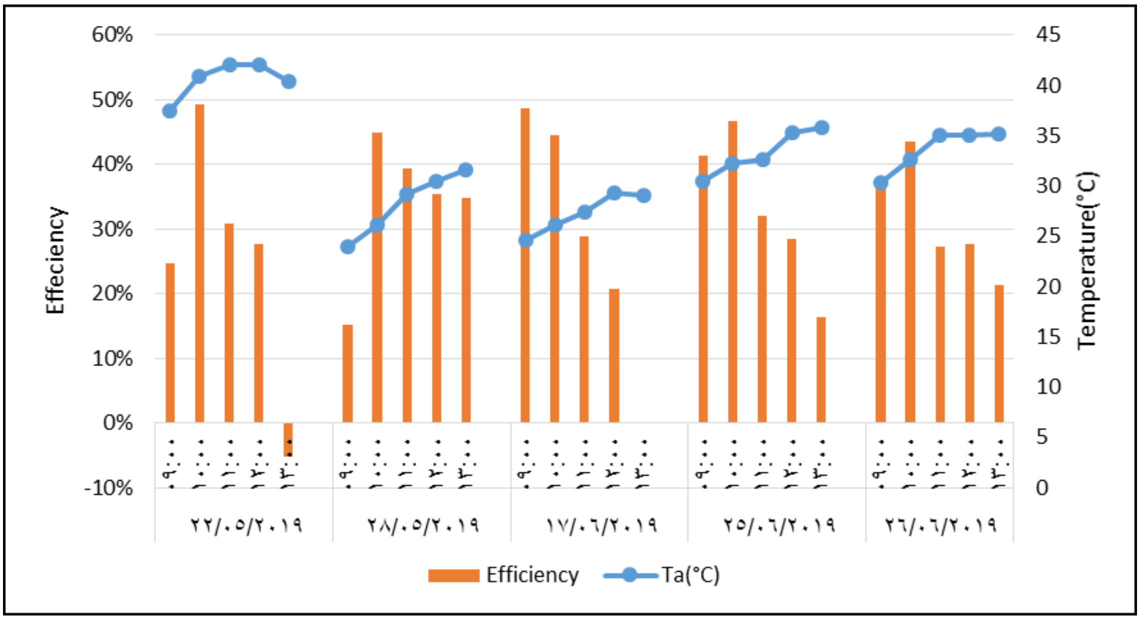

Figure 5.16: Ambient temperature, P-FPC efficiency

By comparing the efficiency of P-FPC and S-FPC, the P-FPC attain higher effeciency than S-FPC during the test days of each type.

3- ETC

As the S-FPC and P-FPC the efficiency of ETC is also highly affected by solar radiation and ambient temperature as shown in Figure 5.17 and Figure 5.18.

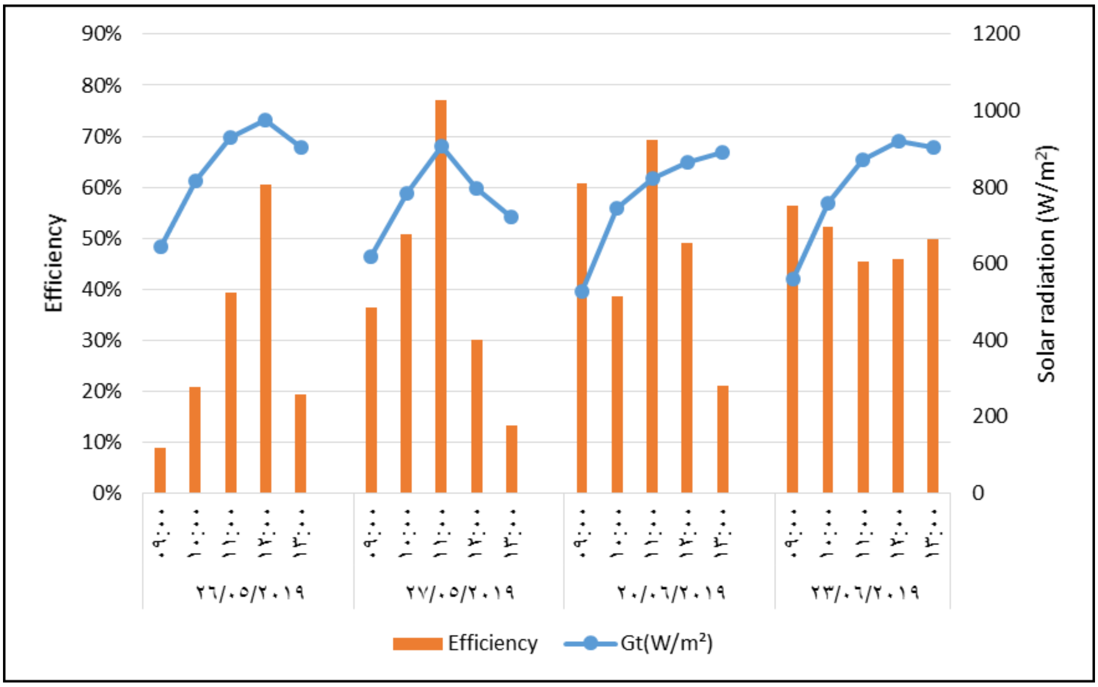

Figure 5.17: Hourly global in-plane solar radiation, ETC efficiency

The maximum hourly efficiency achieved by ETC was 77% and the minimum is 9%.

While the average efficiency was 40% in 26/05/19, 51% in 27/05/2019, 43% in 20/06/19 and 49% in 23/06/19.

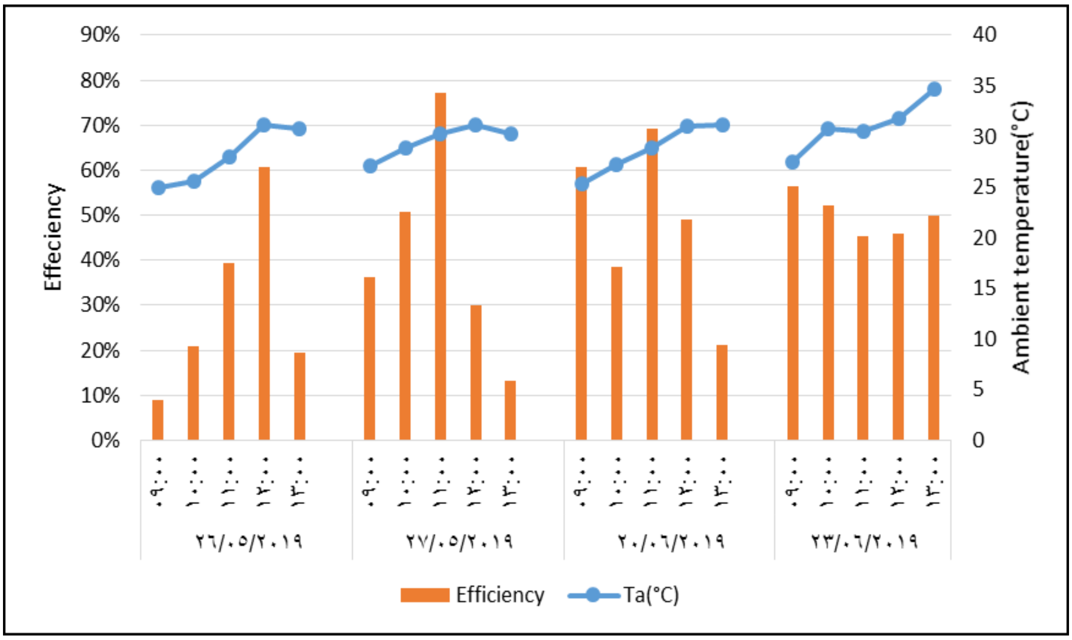

Figure 5.18: Ambient temperature, ETC efficiency

5.5 Thermal efficiency curve:

The thermal efficiency of SWHS with S-FPC, P-FPC and ETC can be expressed as the function of variables $(((T_i-\bar{T}_a)/\bar{G})$ (Pei et al, 2012) as follows:

$$\eta = F_R(\tau\alpha) - F_R U_L\,[(Tin-Ta)/G]$$

The intercept of the efficiency line with the y-axis $F_R(\tau\alpha)$ represents the maximum thermal efficiency of the system. The slop of the efficiency line $F_R U_L$ represents the total heat loss coefficient of the system.

High intercept and small slope mean that the system has good thermal efficiency in the practical conditions (Hu et al.2018).

The hourly efficiency of the system for S-FPC, P-FPC and ETC were calculated using equation:

η_{sys}=m C_p ($\bar{T}_{2tank}$-$\bar{T}_1$tank)

Then the hourly efficiency is plotted against ((Ti-$\bar{T}$a)/$\bar{G}$) and the result appears in figure 5.19

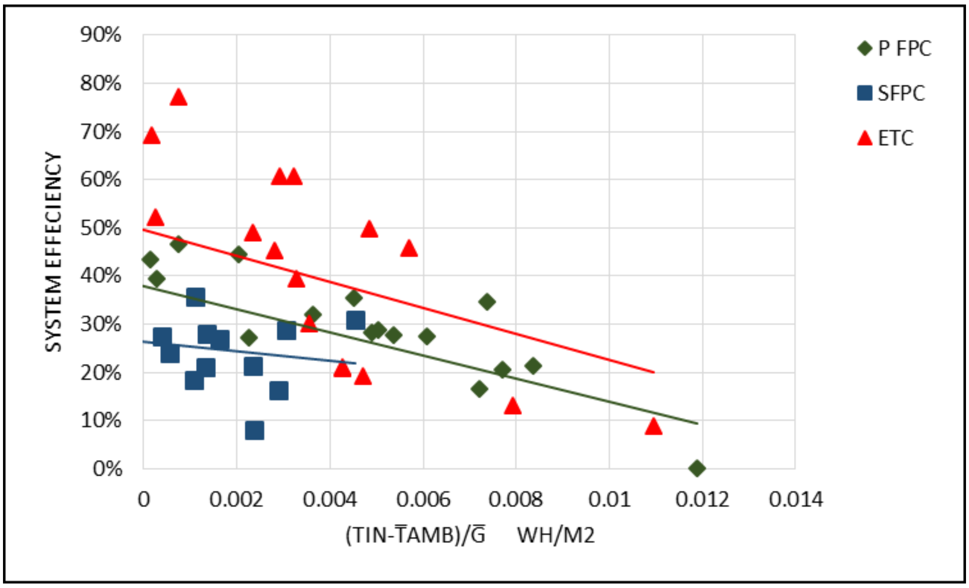

Figure 5.19: Hourly thermal efficiency curves of S-FPC, P-FPC, ETC.

The equation of each curve is:

S-FPC: η_{sys}= 0.2635-10.007((Ti-$\bar{T}$a)/$\bar{G}$)

P-FPC: η_{sys} = 0.3788-23.868((Ti-$\bar{T}$a)/$\bar{G}$)

ETC: η_{sys}= 0.4943-26.917((Ti-$\bar{T}$a)/$\bar{G}$)

From the curves in Figure 5.19, it is found that the maximum thermal efficiency value (η_o) is 0.49 for the ETC, 0.38 for the P-FPC and 0.26 for the S-FPC. It is clearly noted that the ETC is the most efficient one and the P-FPC is more efficient than S-FPC. However, the heat loss coefficient ($-F_RU_L$) for the S-FPC is the less than the P-FPC & ETC this can be attributed to the excellent thermal insulation of the S-FPC.

5.6 Performance comparison at the same weather conditions:

To make a comparison between the three types of collectors in term of daily performance, a three days of similar environmental parameter where chosen for that purpose.

These three days have been chosen to test the three types of collector individually. The P-FPC was tested in 28/5/19, the ETC was tested in 23/6/2019 and the S-FPC was tested in 24/6/19.

5.6.1 Enviornmenal conditions:

Figure5.20 shows that the three days nearly have the same solar radiation and Figure 5.21 shows that the ambient temperature in 24/06/19 is slightly higher than 23/06/19, which also has a slightly higher temperature than 28/05/19. The average solar radiation and ambient temperature for the test period of 28/05/19, 23/06/19, 24/06/19 are (804 w/m^2, 29° C), (791 w/m^2, 31° C) and (796 w/m^2, 32° C) respectively.

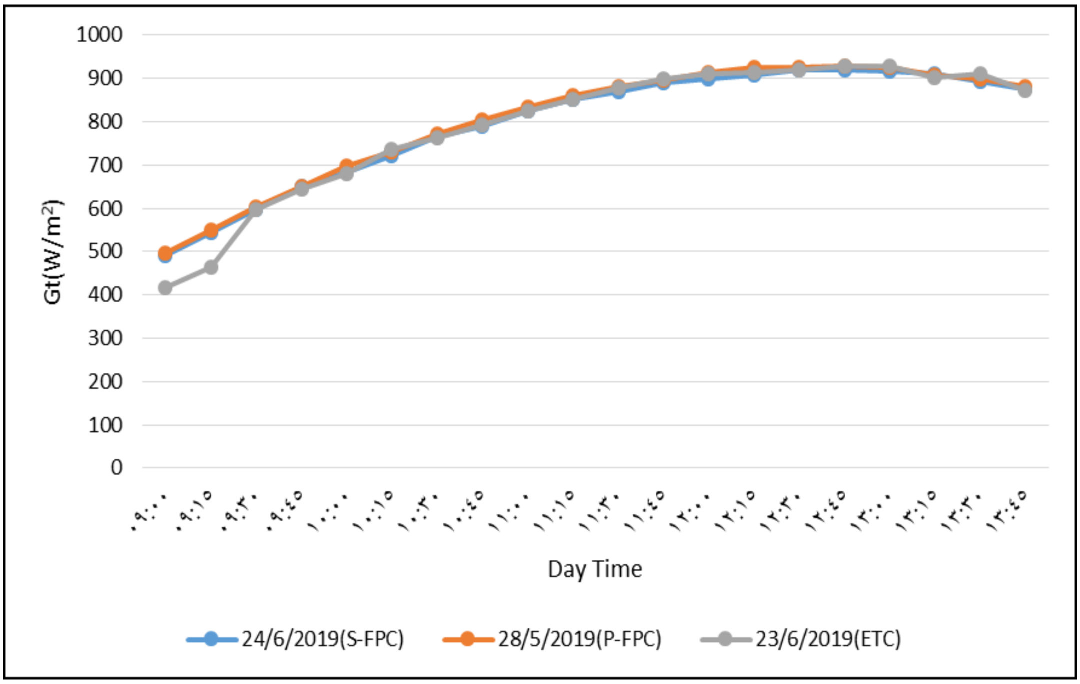

Figure 5.20: In-plane solar radiation for three comparison days

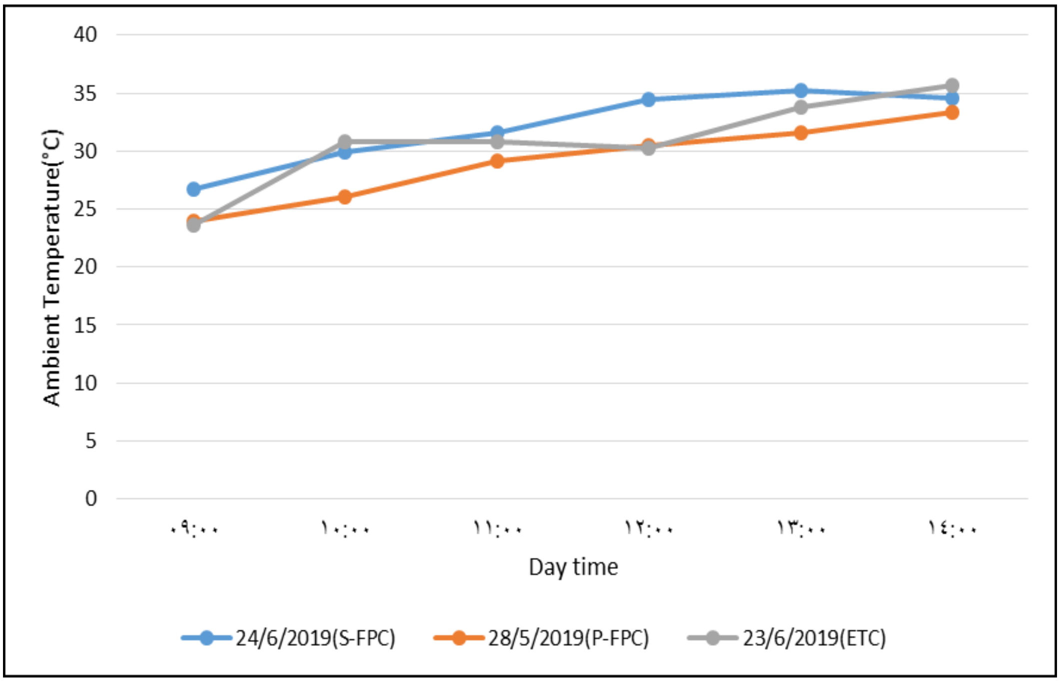

Figure 5.21: Ambient Temperature for three comparison days

5.6.2 Collector inlet-outlet temperatures:

The maximum outlet temperature and the minimum inlet temperature of the collectors, where 51° C/27° C for ETC, 49° C/31° C for S-FPC and 48° C/24° C for P-FPC. The P-FPC raised the water temperature 24° C while S-FPC raised it by 18° C Only. So it is obvious that the P-FPC is more efficient than S-FPC and ETC is the most efficient one especially that it could raise the water temperature by 24° C while as the P-FPC while it has less area.

Figure 5.22 shows the difference between the inlet and the outlet temperatures for the three types of collectors. The ETC has the higher temperature difference up to 12:00 pm then it starts in decreasing due to the decrease in solar radiation. The S-FPC has less temperature difference than the P-FPC up to 10:30 then it starts in having more temperature difference.

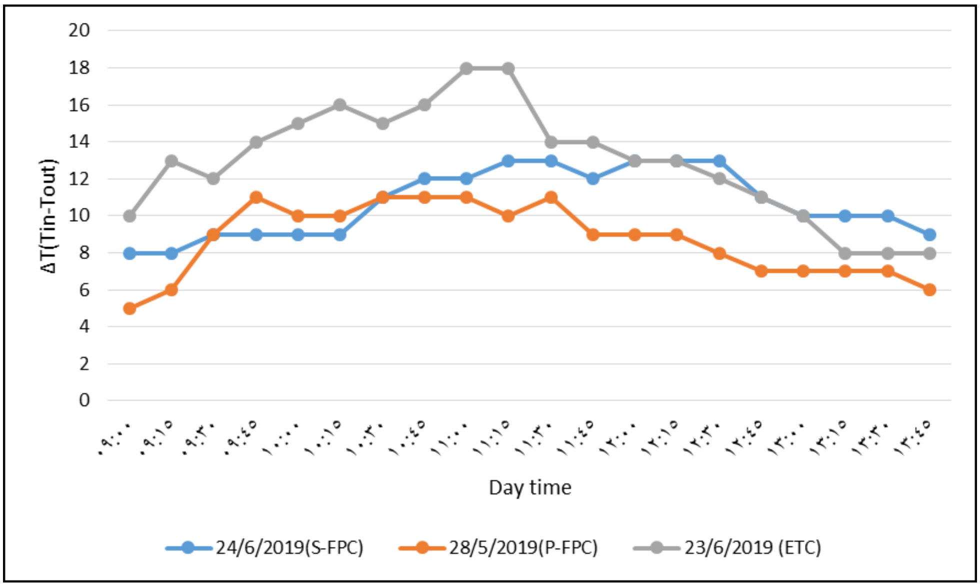

Figure 5.22: ΔT for S-FPC, P-FPC and ETC

5.6.3 Average tank temperature

Figure 5.23 shows the average tank temperature for the three collectors during the three days. The average tank temperature is nearly the same for the three collectors.

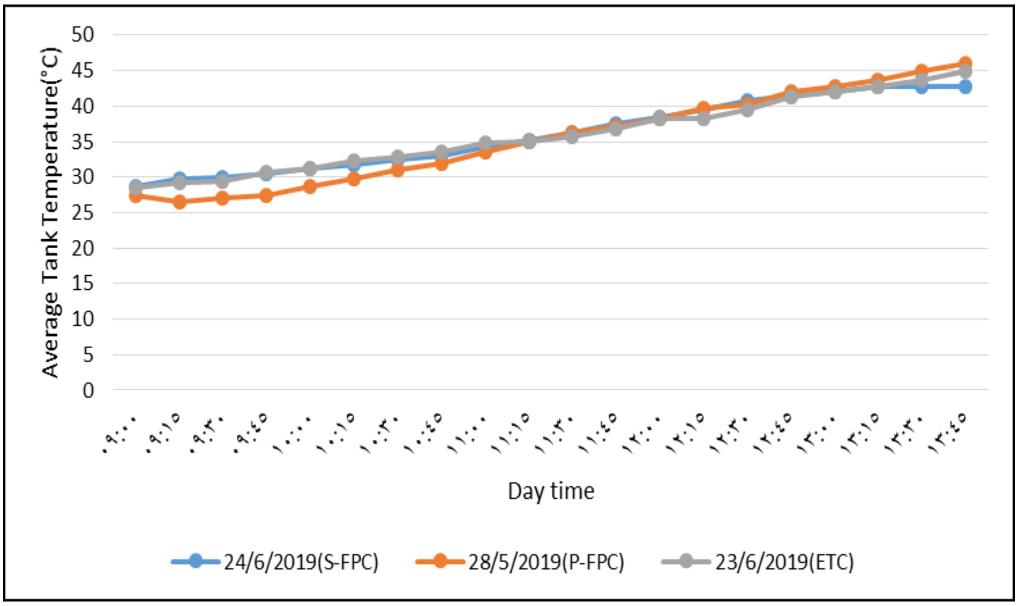

Figure 5.23: Average tank temperature for S-FPC, P-FPC and ETC

5.6.4 Collected energy

Figure 5.24 shows the hourly energy collected by each collector. The ETC attained more energy than the P-FPC and the P-FPC attained more energy than the S-FPC. The total Energy collected by ETC in 23/6/19 from 9:00Am to 1:45 pm was 1854 Wh/m^2 and the useful energy collected by P-FPC was 1415 Wh/m^2 in 28/5/19 while it was 1015 Wh/m^2 for S-FPC in 24/6/19.

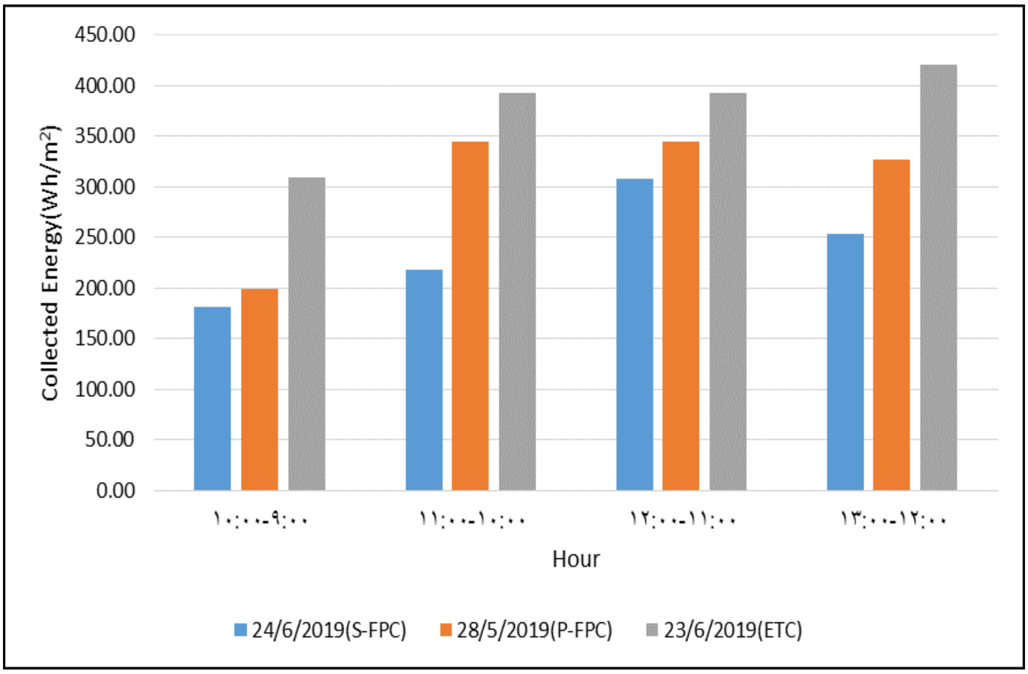

Figure 5.24: Hourly energy collected by S-FPC, P-FPC and ETC.

5.6.5 System efficiency:

The ETC was the most efficient collector of the three. For the period from 9:00 AM and 1:45 PM, the ETC has 49% average efficiency on 23/6/219. 38% is the efficiency of P-FPC in 28/5/19 and 27% for S-FPC in 24/6/19.

Figure 5.24 shows the average hourly efficiency for the three collectors in the three test days.

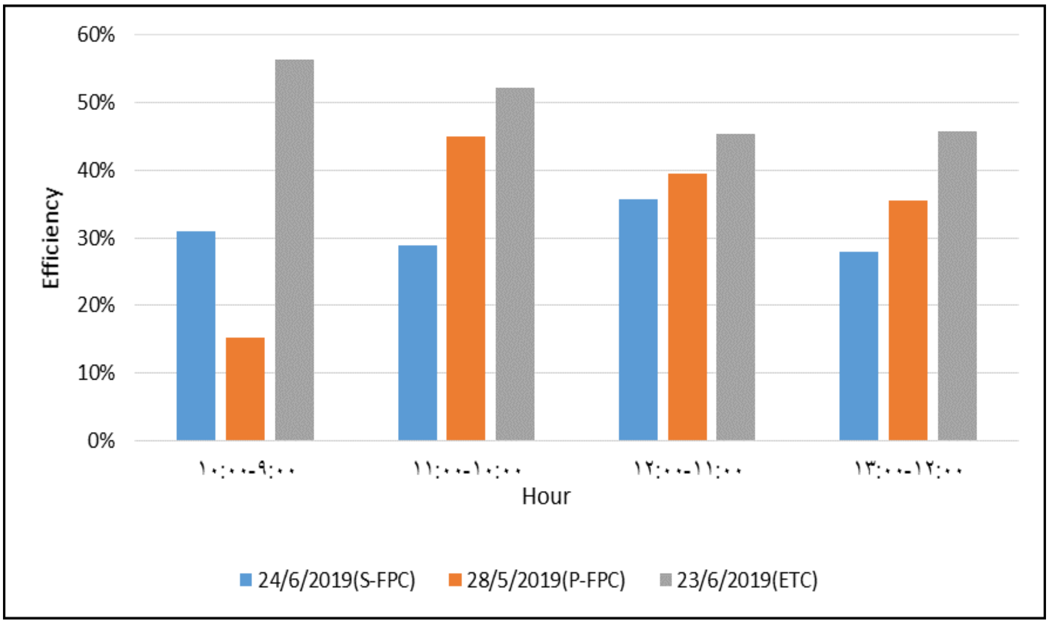

Figure 5.25: Hourly efficiency collected by S-FPC, P-FPC and ETC.

5.7 Simple Pay Pack Period and Net Present Value

The SPP has been calculated for a residential size solar water heater taking into account the performance results obtained from the experiment for each type of collectors.

Based on Palestinian market and residential installation of solar water heaters, the thermosiphon SWHS mostly consists of two FPC connected in parallel each of 1.7 m^2 area and one hot water storage tank of capacity 200 Liter or one U-Pipe ETC with 15 pipes, each with 1.5 m length and 47 mm diameter and a storage tank 150 Liter.

To calculate the SPP for each collector system, the following items must be determined:

1- Capital and running cost of each system.

2- Saving in energy cost per year.

S-FPC and P-FPC systems have the same capital cost which is 1500 NIS. While the ETC system has a capital cost of 3800 NIS.

The thermosiphon SWH system doesn’t need maintenance especially that there are no moving parts such as pumps, and doesn’t consume electricity, so no running costs added for such systems.

The cost of energy saved by SWH is the cost of energy avoided by conventional water heating systems. This study assumed to replace an electrical boiler of 95% efficiency (Yasin, 2017) by the SWH.

The procedure has been followed for calculating the energy saving was described by (Pen et al,2012):

1- Finding the minimum solar radiation (ER_{min}) needed to rise the water temperature from the initial temperature value to final temperature value. The initial water temperature (T1) considered to be 27° C and the Final (T2) is 45° C.

$$ER_{min} = (m \times C_p \times (T2-T1))/(A_c \times \eta_{sys})$$

2- Finding the yearly effective solar radiation (ESR) which is equal:

$ESR=\sum_{1}^{365} ER$

Where;

$ER=ER_{min}$, when $ER_A > ER_{min}$, (ER_A is the actual solar radiation of the day)

$ER= ER_A$, $ER_A < ER_{min}$

Table 5.2 is for the purpose of calculating ESR. It is obtained from pvgis website and shows the average daily solar radiation for each month for Nablus location.

Table 5.4: Average daily solar radiation (PVGIS).

Month	Hh	H(32)	DNI
Jan	2700	3810	2950
Feb	3440	4450	3520
Mar	5110	5910	4780
Apr	6140	6310	5470
May	7450	6920	7240
Jun	8300	7280	8690
Jul	8100	7290	8460
Aug	7420	7330	7830
Sep	6150	6930	6560
Oct	4740	6070	5270
Nov	3330	4710	3860
Dec	2620	3850	3070
Year	5470	5910	5650

Hh: Irradiation on horizontal plane (Wh/m2/day)

H(32): Irradiation on plane at angle: 32deg. (Wh/m2/day)

DNI: Direct normal irradiation (Wh/m2/day)

3- Finding the annual useful energy produced by the SWHS:

Q_u=ESR x η_{sys} x A_c

4- Estimating the annual revenues using equations 19 and 20:

R= Q_u x E_{tariff} / η_{boiler}

Where E_{tariff}: 0.62 NIS/kWh (Source: Northern Electricity Distribution Co)

η_{boiler} is the efficiency of the Electrical boiler.

Based on the above equations, the obtained results for each collector type are shown in Table 5.3:

Table 5.5: Energy saving cost by S-FPC, P-FPC and ETC.

#	Collector type	η_{sys}	A_c (m^2)	ER_{min} ($kWh/m^2/day$)	ESR ($kWh/m^2/year$)	Es (kWh /year)	R (NIS/ year)
1	S-FPC	26%	3.4	4.728	1661	1468	958
2	P-FPC	38%	3.4	3.235	1180	1525	995
3	ETC	49%	1.3	4.9	1708	1088	710

And Table 5.4 shows the expenses, revenues and SPP for each type of collectors based on equations 17, 21 and 22. Knowing that the lifetime is 20 years for each collectors

Table 5.6: Cash flow for the S-FPC, P-FPC and ETC.

#	Collector type	C_0 (NIS)	$C_{running}$ (NIS)	Rt over 20 years (NIS)	NPV (NIS)		SPP (year)
1	S-FPC	1500	0	19160	17660		1.56
2	P-FPC	1500	0	19900	18400		1.5
3	ETC	3800	0	14200	10400		5.35

The results show that the three types of collectors are economically viable. The P-FPC has the less payback period in comparison with the other two collectors. This can explain the large number of its installations in Palestine not like the S-FPC and ETC.

Chapter Six

Conclusion and Recommendations

6.1 Conclusion

A comparison of the experimental prototype of solar water heating systems with ETC, S-FPC and P-FPC was conducted. The results of the comparative tests were presented.

This study compares also between the performance of ETC, S-FPC and P-FPC systems under the same weather conditions. Results show that the daily energy collected by S-FPC is 1015 Wh/m^2, 1415 Wh/m^2 for P-FPC and 1854 Wh/m^2 for ETC. The system efficiencies was 26%, 38% and 49% for S-FPC, P-FPC and ETC respectively.

Economic analysis shows that all SWHSs are economically feasible with NPV and SPP 17660 NIS, 1.56 years for S-FPC, 18400NIS, 1.5 years for P-FPC and 10400 NIS, 5.35 years for ETC.

From the obtained results, we notice that the ETC system is the most efficient one between the three systems but it still has high initial cost in comparison with S-FPC and P-FPC.

In Palestine, most people chose the FPC for household applications because of its cheap price and its effectiveness in covering hot water demand of houses.

But the commercial and industrial facilities start in using the ETC system since it can give water at very high temperature for different applications such as heating water, pool heating and space heating even in winter and then it reduces the huge electrical bills come from using fossil fuels for heating water. This make the ETC more economically feasible to be used commercial and industrial applications than residential applications.

6.2 Recommendations

1- In order to achieve the General Renewable Energy Strategy in terms of solar thermal plants and to achieve 20MW from these plants up to 2020. The Palestinian government should enact legations that encourage all sectors (residential, commercial and industrial) to build their own solar thermal plants in order to cover their thermal loads.

2- The thermal energy that has been obtained from the solar water heating systems in Palestine are cheap, clean and reliable. Therefore, the Palestinian government should pay more attention to this energy and should seek for covering as much as possible of thermal loads from solar energy.

3- Although Palestine is a leading country in using SWHSs, but it can be noticed that the use of SWHS is constantly decreasing. So, awareness must be spread among people about the benefits of using SWHS.

4- Palestinian standard institute (PSI) should build labs for testing the solar collectors that are imported or locally made and used in Palestinian markets, in order to keep a high quality of collectors. The PSI should also update the testing standards of SWHSs since the last update was in 1997.

5- Evacuated tube collectors proved their high performance in comparison to the flat plate collectors, but they are still not familiar in Palestinian market. So, the awareness for the evacuated tube should be increased.

6- More research should be done on the technical and the economical feasibility of using SWHSs in all sectors and the positive results will encourage decision makers to go ahead in installing such systems.

References

- Abdulrazaq, M., Alghoul, M., Abulqasem, Kh., Mustafa, A., Glaisa, kh., Ooshaksaraei, P., Yahya, M., Zaharim, A., Sopian, K. 2011. **TRNSYS Simulation of Solar Water Heating System in Iraq.** Conference Paper, DOI: 10.13140/2.1.1979.8724.

- Ahmed, M., Amin, A. 2016. ***Thermal Analysis of the Performance of Linear Fresnel Solar Concentrator*. Journal of Clean Energy Technologies**, Vol. 4, No. 5.

- Akanmu, W. P. Bajere, P. A. 2015. ***Investigation of Temperature and Flow Distribution in a Serially Connected Thermosyphon Solar Water Heating Collector System in Minna, Niger State, Nigeria*. Journal of Energy Technologies and Policy**, ISSN 2224-3232, Vol.5, No.2.

- Alghoul, M., Sulaiman, M., Azmi, B., and Abd. Wahab, M. 2005. **Review of materials for solar thermal collectors**. Anti-Corrosion Methods and Materials, Volume 52, Number 4, 199–206.

- Alkishriwi1, N., Schorn, Ch., Theis, D. 2014. **The International Standards for Solar Thermal Collectors and Components as a Medium of Quality Assurance.** Solar Energy and Sustainable Development, Volume (3) No (1).

- Almasri, R., Almarshoud, A. 2017. ***Feasibility of Using Evacuated Tube Solar Water Heaters in Saudi Arabia*. European Journal of Advances in Engineering and Technology,** 4 (4): 232-241.

- Alternative energy tutorials. 2019. **http://www.alternative-energy-tutorials.com/solar-hot-water/evacuated-tube-collector.html.**

- Alternative energy tutorials. 2019. **http://www.alternative-energy-tutorials.com/solar-hot-water/integral-collector-storage.html.**

- Amrutkar, S., Ghodke, G., Patil, k. 2012. **Solar Flat Plate Collector Analysis.** IOSR Journal of Engineering (IOSRJEN), Vol. 2 Issue 2, pp.207-213.

- Appropedia, 2007. **https://www. appropedia.org/File:Thermosyphon.gif.**

- Apricus Solar. 2013. **www.Apricus-solar.com.**

- Ayompe, L., Duffy, A. 2013. **Analysis of the Thermal Performance of a Solar Water Heating System with Flat Plate Collectors in a Temperate Climate.** 58, 447-454. doi:10.1016/j.applthermaleng.2013.04.062.

- Ayompe, L., Duffy, A. 2013. **Thermal Performance Analysis of a Solar Water Heating System With Heat Pipe Evacuated Tube Collector Using Data From a Field Trial.** Solar Energy: 90; 17-28.

- Ayompe, L., Duffy, A., McCormack, S., McKeever, M., Conlon, M. 2011. **Comparative Field Performance Study of Flat Plate and Heat Pipe Evacuated Tube Collectors (ETCs) for Domestic Water Heating Systems in a Temperate Climate**. Energy, Vol. 36, Issue 5, pp. 3370-3378.

- Azimi, M., Mirjavadi, S., Mohammadkarim, A. 2016**. *Simulation and Optimization of Vacuum Tube Solar Collector Water Heating System in Iran.* Journal of Science and Engineering**; Vol. 07 (01), 001-019**.**

- Bhamare, K., Rathod, M., Banerjee, J. 2018. ***Performance Evaluation of Thermosiphon Based Solar Water Heater in India***. **International Journal of Energy and Power Engineering** Vol:12, No:1.

- Bisla, M., Mor, P. 2017. ***Experimental analysis of Evacuated Tube Collector with parabolic and flat reflectors*. International Journal of Research in Management, Science & Technology**, Vol. 5, No. 1, 109-114.

- Budihardjo, I., Morrison, G. L., & Behnia, M. 2007. **Natural circulation flow through water-in-glass evacuated tube solar collectors.** Solar Energy, 81(12), 1460–1472. doi:10.1016/j.solener.2007.03.002

- Esen, M., Esen, H. 2005. **Experimental investigation of a two-phase closed thermosyphon solar water heater.** Solar Energy 79, 459–468.

- Fischer, S., Muller-Steinhagen, H. 2001. **Collector test method under quasi-dynamic conditions according to the European Standard EN 12975-2.** ISES Solar world congress, Germany.

- Gautam, A., Chamoli, S., Kumar, A., & Singh, S. 2017. **A review on technical improvements, economic feasibility and world scenario of solar water heating system.** Renewable and Sustainable Energy Reviews, 68, 541–562. doi:10.1016/j.rser.2016.09.104.

- Gowda, N., Gowda, B., Chandrashekar, R. 2014. ***Investigation of Mathematical Modelling to Assess the Performance of Solar Flat Plate Collector.*** **International journal of renewable energy research**. Vol.4, No.2.

- Günther, M., Joemann, M., Csambor, S. 2011. **Advanced CSP Teaching Materials**. University of Kassel, Wilhelmshöher.

- Hayek, M., Assaf, J., Lteif, W. 2011. **Experimental Investigation of the Performance of Evacuated- Tube Solar Collectors under Eastern Mediterranean Climatic Conditions.** Energy Procedia 6, 618–626.

- Hernández, E., Guzmán, R. 2016. ***Comparison of three systems of solar water heating by thermosiphon*. Journal of Physics: Conference Series** 687, 012007.

- Hossain, M.S., Saidur, R., Fayaz, H., Rahim, N.A., Islam, M.R., Ahamed, J.U., Rahman, M.M., 2011. **Review on solar water heater collector and thermal energy performance of circulating pipe.** Renewable and Sustainable Energy Reviews, 15, 3801– 3812.

- Hua, Z., Luo ,B., He, W., Hub, D., Ji, J., Mac, J. 2018.**Performance study of a dual-function roof solar collector for Chinese traditional buildings application.** Applied Thermal Engineering 128,179–188.

- Ibrik, I., & Mahmoud, M. (2005). **Energy efficiency improvement procedures and audit results of electrical, thermal and solar applications in Palestine**. Energy Policy, 33(5), 651–658. doi:10.1016/j.enpol.2003.09.008.

- Ibrik, I., Mahmoud, M. 2005**. Energy efficiency improvement procedures and audit results of electrical, thermal and solar applications in Palestine.** Energy Policy 33, 651–658.

- Juaidi, A., Montoya, F.G., Ibrik, I.H., Manzano-Agugliaro, F. 2016. **An overview of renewable energy potential in Palestine.** Renewable and Sustainable Energy Reviews, 65, 943–960.

- Kalogirou, S. 2004. **Solar thermal collectors and applications**. Progress in Energy and Combustion Science, 30, 231–295.

- Koffia, P., Andoh, H., Gbaha, P., Toure´, S., Ado, G. 2008. **Theoretical and experimental study of solar water heater with internal exchanger using thermosiphon system.** Energy Conversion and Management 49, 2279–2290.

- Kong, W. Wang, Zh., Fan, J. Peres, B. Chen, Z. Furbo, S., Anderson, E. 2012. **Investigation of thermal performance of flat plate and evacuated tubular solar collectors according to a new dynamic test method.** Energy Procedia 30, 152 – 161**.**

- Kovacs, P. 2012. **A guide to the standard EN 12975.** Technical Research Institute of Sweden, Deliverable D2.3.

- Mishra, D. 2015. **Experimental Analysis of Thermal Performance of Evacuated U-Tube Solar Collector.** Advance Physics Letter, Vol 2, Issue 3, 2349-1108.

- Mohammad karim, A., Kasaeian, A., Kaabinejadian,A. 2014. ***Performance Investigation of Solar Evacuated Tube Collector Using TRNSYS in Tehran*. International journal of renewable energy research**. Vol.4, No.2.

- Morrison, G, Budihardjo, I, Behnia, M. 2004. **Measurement and simulation of flow rate in a water-in-glass evacuated tube solar water heater.** Solar Energy 78, 257–267.

- Morrison, G., Budihardjo, I., Behnia, M. 2004. **Water-in-glass evacuated tube solar water heaters.** Solar Energy 76, 135–140.

- Nájera-Trejoa, M., Martin-Domíngueza, I., Escobedo-Bretadoa, J. 2016. **Economic feasibility of flat plate vs evacuated tube solar collectors in a combisystem.** Energy Procedia 91, 477 – 485.

- Nijaguna, B., 1992. **Thermal Sciences/Engineering data book**. 1st ed. Allied Publishers Limited, New Delhi, p. O-18.

- Osórioa, T., Carvalhoa, M. 2012. **Testing of solar thermal collectors under transient conditions.** Energy Procedia 30, 1344 – 1353.

- Palestinian Central Bureau of statistics (PCBS). **Percentage Distribution of Households by Region, Availability and usage of Solar Heater, 2015.** Retrieved from PCBS website: https://www.pcbs.gov.ps/Portals/_Rainbow/Documents/HE-%20EA4%202015.htm

- Palestinian Central Bureau of statistics (PCBS). **Quantity of Electricity Imported and Purchased in Palestine, 2017.** Retrieved from PCBS website: https://www.pcbs.gov.ps/Portals/_Rainbow/Documents/electricity-2017-3E.html.

- Pan, T., Kao, J., Wong, C., 2012. **Effective solar radiation based benefit and cost analyses for solar water heater development in Taiwan.** Renewable and Sustainable Energy Reviews 16, 1874– 1882.

- Pei, G., Li, G., Zhou, X., Ji, J., Su, Y., 2012**. Comparative Experimental Analysis of the Thermal Performance of Evacuated Tube Solar Water Heater Systems With and Without a Mini-Compound Parabolic Concentrating (CPC) Reflector(C < 1).** Energies, *5*, 911-924; doi:10.3390/en5040911.

- Sabiha, M., Saidur, R., Mekhilef, S., Mahian, O. 2015. **Progress and latest developments of evacuated tube solar collectors.** Renewable and Sustainable Energy Reviews 51, 1038–1054.

- Sadaq, S.I., Mehdi, N., Ishrath, M.M, Mehar, A., Kumari, NBV.L. 2015. ***Performance analysis of solar flat plate collector***. **International Journal of Mechanical And Production Engineering,** Vol. 3, Issue 5, 2320-2092.

- Sarbu, L., Sebarchievici, C. 2017. **Solar Heating and Cooling Systems.** Academic Press, 1 edition, ISBN: 9780128116623.

- Shariah, A., Al-Akhras, M., Al-Omari, I. 2002. **Optimizing the tilt angle of solar collectors.** Renewable Energy 26, 587–598.

- Shitzer, A., Kalmanoviz, D., Zvirin, Y., Grossman, G. 1979. **Experiments with a flat plate solar water heating system in thermosyphonic flow.** Solar Energy Vol. 22, pp. 27-35.

- Solar panels plus. 2014. **http://www.solarpanelsplus.com/evacuated-tube-collectors/.**

- Struckmann, F. 2008. **Analysis of a Flat-plate Solar Collector.** Report, Lund University, Sweden, May.

- Tambunan, D., Sibagariang, Y., Ambarita, H., Napitupulu, F., Kawai, H. 2018. ***Numerical study on the effects of absorptivity on performance of flat plate solar collector of a water heater***. **Journal of Physics: Conf. Series** 978, 012099.

- Wang, K., Cheng, Y., Zhang, Ch. 2018. **Experimental Study on the Effect of Solar Radiation on Heat Transfer Performance of Flat panel Solar Water Heater.** Radiation research.

- Weiss, W., Spörk - Dür, M., Mauthner, F. 2018. **Solar Heat Worldwide**. Austria: AEE INTEC.

- **Worldometers. 2019**. Retrieved from Worldometers website: https://www.worldometers.info/world-population/

- Yasin, A. 2017. **Technical and Financial Assessment of Glazed and Evacuated Tubes Solar Collectors for Domestic Water Heating Application in Palestine.** An - Najah Univ. J. Res. (N. Sc.) Vol. 13(1).

- Yasin, A., Alsayed, M., Yasin, B., Arafat, H. 2011. **Evaluation of energy and CO_2 saving of an institutional collective solar water heating system in Palestine.** Resouk 2011, Emuni student research multi-conference.

- Zambolin, E., Del Col, D. 2010. **Experimental analysis of thermal performance of flat plate and evacuated tube solar collectors in stationary standard and daily conditions**. Solar Energy 84, 1382–1396.

Appendices

Appendix A: Experimental collected data.

Date:		**22/05/2019**							
Collector Type :		**P-FPC**							
Collector area:		**0.48m2**							
Tilt Angle:		**32**							
		Collector Temperatures		**Tank Temperatures**					
#	**Hour**	**T1:T_{in}**	**T2:T_{out}**	**T3**	**T4**	**T5**	**T6**	**$\bar{T}$tank**	**G_{global}(w/m2)**
1	09:00	38	41	39	39	39	40	39.25	476
2	09:15	39	44	39	39	39	40	39.25	531.67
3	09:30	40	46	39	39	39	41	39.5	580.33
4	09:45	40	47	39	40	40	43	40.5	631.33
5	10:00	40	48	39	40	42	44	41.25	695.5
6	10:15	40	48	40	41	44	45	42.5	722
7	10:30	40	50	41	43	46	46	44	779.33
8	10:45	41	50	42	45	47	47	45.25	799
9	11:00	42	52	44	46	48	48	46.5	852.33
10	11:15	44	52	46	48	49	49	48	868
11	11:30	45	55	47	48	50	50	48.75	900.67
12	11:45	46	53	47	49	50	50	49	908
13	12:00	47	55	48	50	52	51	50.25	909.33
14	12:15	47	54	49	51	52	51	50.75	890.33
15	12:30	48	55	50	52	53	52	51.75	913
16	12:45	49	55	52	53	54	52	52.75	939
17	13:00	49	54	53	54	55	53	53.75	930.33
18	13:15	50	53	53	54	55	53	53.75	916.67
19	13:30	50	53	54	55	55	51	53.75	893.33
20	13:45	49	50	54	54	55	50	53.25	882.67
								Avg:	800.941

Date:			**28/05/2019**						
Collector Type :			**P-FPC**						
Collector area:			**0.48m2**						
Tilt Angle:			**32**						
		Collector Temperatures		**Tank Temperatures**					
#	**Hour**	**$T1:T_{in}$**	**$T2:T_{out}$**	**T3**	**T4**	**T5**	**T6**	**$\bar{T}_{tank}$**	**G_{global}(w/m2)**
1	09:00	24	29	26	27	28	29	27.5	497.67
2	09:15	26	32	25	26	27	28	26.5	549.67
3	09:30	26	35	25	27	28	28	27	603.33
4	09:45	26	37	26	27	28	29	27.5	649.67
5	10:00	27	37	27	28	29	31	28.75	698
6	10:15	28	38	27	29	31	32	29.75	729.33
7	10:30	29	40	28	30	33	33	31	771
8	10:45	29	40	29	31	34	34	32	803
9	11:00	30	41	30	33	36	35	33.5	833.67
10	11:15	31	41	32	34	36	38	35	861
11	11:30	32	43	34	36	38	37	36.25	881.67
12	11:45	34	43	35	37	39	38	37.25	895.67
13	12:00	35	44	36	38	40	39	38.25	915
14	12:15	37	46	38	39	41	41	39.75	925.33
15	12:30	37	45	39	40	42	40	40.25	924.67
16	12:45	38	45	40	42	44	42	42	930
17	13:00	39	46	41	43	45	42	42.75	925.67
18	13:15	40	47	42	44	46	43	43.75	908.67
19	13:30	41	48	44	45	47	44	45	899.33
20	13:45	42	48	45	46	47	46	46	881.67
								Avg:	804.201

Date:		17/06/2019							
Collector Type :		P-FPC							
Collector area:		0.48m2							
Tilt Angle:		32							
		Collector Temperatures		Tank Temperatures					
#	Hour	T1:T_{in}	T2:T_{out}	T3	T4	T5	T6	$\bar{T}_{tank}$	G_{global}(w/m2)
1	09:00	25	29	25	26	27	27	26.25	366.33
2	09:15	25	30	26	27	28	28	27.25	301.67
3	09:30	27	35	27	28	29	29	28.25	437
4	09:45	27	37	28	28	30	30	29	622
5	10:00	28	36	28	29	31	30	29.5	600.67
6	10:15	28	37	28	29	31	30	29.5	785
7	10:30	29	38	29	30	32	31	30.5	555
8	10:45	29	39	30	31	33	31	31.25	480.33
9	11:00	32	41	32	34	35	32	33.25	620
10	11:15	32	42	34	35	35	33	34.25	570.33
11	11:30	34	43	35	35	37	35	35.5	939
12	11:45	35	42	35	36	38	35	36	657
13	12:00	35	44	35	37	39	35	36.5	1012
14	12:15	35	42	36	38	40	36	37.5	505
15	12:30	36	42	37	39	40	37	38.25	805.67
16	12:45	36	41	38	39	40	36	38.25	807
17	13:00	37	40	39	40	40	36	38.75	570.67
18	13:15	37	42	39	40	40	36	38.75	628
19	13:30	38	43	39	40	40	36	38.75	727
20	13:45	38	41	39	40	40	36	38.75	761
								Avg:	637.5335

Date:			**25/06/2019**						
Collector Type :			**P-FPC**						
Collector area:			**0.48m2**						
Tilt Angle:			**32**						
		Collector Temperatures		**Tank Temperatures**					
#	**Hour**	**$T1:T_{in}$**	**$T2:T_{out}$**	**T3**	**T4**	**T5**	**T6**	**$\bar{T}tank$**	**G_{global}(w/m2)**
1	09:00	30	38	30	31	32	33	31.5	474.33
2	09:15	31	40	30	32	31	34	31.75	524.67
3	09:30	32	41	31	32	34	35	33	576
4	09:45	33	41	32	33	35	36	34	624
5	10:00	33	43	32	34	36	37	34.75	666.67
6	10:15	34	43	33	35	38	38	36	712.5
7	10:30	34	43	34	37	39	38	37	744.67
8	10:45	35	44	36	38	40	39	38.25	779
9	11:00	37	46	37	39	41	41	39.5	809.33
10	11:15	37	46	39	40	42	41	40.5	834
11	11:30	39	48	40	41	43	43	41.75	860.67
12	11:45	40	49	41	42	44	44	42.75	878.67
13	12:00	40	48	42	43	45	43	43.25	888.5
14	12:15	41	49	43	44	45	44	44	899.33
15	12:30	42	49	44	45	46	45	45	903.67
16	12:45	42	49	45	46	47	45	45.75	906.67
17	13:00	43	49	46	47	48	46	46.75	901
18	13:15	43	48	46	47	48	45	46.5	893.33
19	13:30	44	49	47	48	49	46	47.5	878
20	13:45	44	49	48	48	49	48	48.25	863.33
								Avg:	780.917

Date:		**26/06/2019**							
Collector Type :		**P-FPC**							
Collector area:		**0.48m2**							
Tilt Angle:		**32**							
		Collector Temperatures		**Tank Temperatures**					
#	**Hour**	**$T1:T_{in}$**	**$T2:T_{out}$**	**T3**	**T4**	**T5**	**T6**	**$\bar{T}$tank**	**G_{global}(w/m2)**
1	09:00	31	39	31	32	33	34	32.5	475.33
2	09:15	32	40	31	32	34	35	33	530.67
3	09:30	33	41	32	33	34	35	33.5	581
4	09:45	33	42	33	34	36	37	35	631
5	10:00	34	42	33	35	37	37	35.5	676.67
6	10:15	35	44	34	36	38	38	36.5	725.5
7	10:30	35	44	36	38	39	39	38	755.67
8	10:45	36	44	37	38	40	39	38.5	794
9	11:00	37	46	38	40	41	41	40	824.67
10	11:15	38	47	39	41	42	41	40.75	852
11	11:30	39	47	40	41	43	41	41.25	874
12	11:45	41	47	40	42	44	41	41.75	895.5
13	12:00	40	48	42	43	45	43	43.25	906.33
14	12:15	41	49	43	44	45	44	44	915.67
15	12:30	42	49	44	45	46	45	45	924.33
16	12:45	42	49	45	46	47	45	45.75	925.67
17	13:00	43	49	46	47	48	46	46.75	926.33
18	13:15	43	48	46	47	48	45	46.5	916
19	13:30	44	49	47	48	49	46	47.5	906
20	13:45	44	50	48	49	50	48	48.75	888.33
								Avg:	796.2335

Date:		**29/05/2019**							
Collector Type :		**S-FPC**							
Collector area:		**0.48m2**							
Tilt Angle:		**32**							
		Collector Temperatures		**Tank Temperatures**					
#	**Hour**	**T1:T_{in}**	**T2:T_{out}**	**T3**	**T4**	**T5**	**T6**	**$\bar{T}_{tank}$**	**G_{global}(w/m2)**
1	09:00	31	38	29	30	31	33	30.75	495
2	09:15	33	40	29	30	31	33	30.75	548.67
3	09:30	33	41	30	31	31	34	31.5	599
4	09:45	34	43	30	31	32	35	32	650.67
5	10:00	34	45	31	32	32	37	33	697
6	10:15	35	47	31	32	34	39	34	743.5
7	10:30	35	48	32	33	35	40	35	773
8	10:45	35	48	32	33	36	41	35.5	807.33
9	11:00	35	49	32	34	37	42	36.25	837.67
10	11:15	36	50	33	35	39	43	37.5	862.33
11	11:30	35	48	33	36	40	42	37.75	880.33
12	11:45	36	49	34	37	41	42	38.5	899.5
13	12:00	36	49	35	39	43	44	40.25	907.33
14	12:15	37	50	36	39	43	43	40.25	917.67
15	12:30	37	50	37	41	45	45	42	922
16	12:45	37	48	39	42	45	44	42.5	921.33
17	13:00	38	48	40	43	46	44	43.25	913
18	13:15	38	48	41	44	46	44	43.75	899.5
19	13:30	38	49	42	45	47	45	44.75	888.67
20	13:45	39	49	42	45	47	45	44.75	873
								Avg	801.825

Date:			**30/05/2019**						
Collector Type :			**S-FPC**						
Collector area:			**0.48m2**						
Tilt Angle:			**32**						
		Collector Temperatures		**Tank Temperatures**					
#	**Hour**	**T1:T_{in}**	**T2:T_{out}**	**T3**	**T4**	**T5**	**T6**	$\bar{T}_{tank}$	**G_{global}(w/m2)**
1	09:00	35	41	34	35	36	38	35.75	482
2	09:15	37	44	34	35	36	38	35.75	534.33
3	09:30	37	46	35	36	36	38	36.25	582.67
4	09:45	38	47	35	36	37	39	36.75	634
5	10:00	38	47	35	36	37	40	37	672.33
6	10:15	38	48	36	37	38	41	38	716.33
7	10:30	39	52	37	38	39	43	39.25	755.33
8	10:45	40	53	37	38	40	45	40	790.33
9	11:00	40	54	38	39	42	47	41.5	822.67
10	11:15	40	54	38	40	43	48	42.25	853.5
11	11:30	40	54	39	41	45	49	43.5	872.33
12	11:45	41	54	39	42	46	50	44.25	888.33
13	12:00	41	53	40	44	48	50	45.5	902
14	12:15	41	54	41	44	48	49	45.5	905.33
15	12:30	42	53	43	46	50	52	47.75	914.33
16	12:45	42	53	45	48	51	53	49.25	905.5
17	13:00	43	55	46	49	52	54	50.25	909
18	13:15	44	54	47	50	53	53	50.75	897.67
19	13:30	45	55	49	51	53	54	51.75	874.33
20	13:45	45	56	50	52	53	55	52.5	864
								Avg:	788.8

Date:	10/06/2019								
Collector Type :	S-FPC								
Collector area:	0.48m2								
Tilt Angle:	32								
		Collector Temperatures		Tank Temperatures					
#	Hour	T1:T_{in}	T2:T_{out}	T3	T4	T5	T6	$\bar{T}_{tank}$	G_{global}(w/m2)
1	09:00	31	40	28	30	30	32	30	509.67
2	09:15	32	41	28	30	30	33	30.25	565
3	09:30	32	41	29	30	31	34	31	618.33
4	09:45	32	43	29	31	31	35	31.5	674
5	10:00	32	43	30	31	32	36	32.25	705.67
6	10:15	32	43	30	31	33	36	32.5	750.67
7	10:30	33	44	30	32	34	37	33.25	786.67
8	10:45	33	45	31	32	35	38	34	822.33
9	11:00	33	44	31	33	36	38	34.5	846.67
10	11:15	33	45	32	34	37	38	35.25	883
11	11:30	33	45	32	34	37	38	35.25	901
12	11:45	33	46	33	35	38	39	36.25	919
13	12:00	33	47	33	36	39	39	36.75	927
14	12:15	33	48	35	38	39	39	37.75	934
15	12:30	34	48	36	38	40	40	38.5	940
16	12:45	34	44	37	39	41	41	39.5	947
17	13:00	35	44	38	40	42	41	40.25	928.33
18	13:15	35	44	38	40	43	40	40.25	915.67
19	13:30	36	46	39	42	44	42	41.75	898.67
20	13:45	37	47	40	42	44	43	42.25	890.33
								Avg	818.1505

Date:		24/06/2019							
Collector Type :		S-FPC							
Collector area:		0.48m2							
Tilt Angle:		32							
		Collector Temperatures		Tank Temperatures					
#	Hour	T1:T_{in}	T2:T_{out}	T3	T4	T5	T6	$\bar{T}_{tank}$	G_{global}(w/m2)
1	09:00	31	39	27	28	29	31	28.75	491
2	09:15	31	39	28	29	30	32	29.75	545.33
3	09:30	32	41	28	29	30	33	30	597.67
4	09:45	32	41	28	29	30	35	30.5	649.5
5	10:00	33	42	29	30	31	35	31.25	682.67
6	10:15	33	42	29	30	32	36	31.75	720.67
7	10:30	33	44	30	31	33	36	32.5	764.67
8	10:45	33	45	30	31	34	37	33	790.33
9	11:00	34	46	31	32	35	39	34.25	825.67
10	11:15	34	47	31	33	37	40	35.25	851
11	11:30	35	48	32	34	38	41	36.25	871
12	11:45	36	48	33	36	39	42	37.5	889
13	12:00	36	49	34	37	40	43	38.5	899.33
14	12:15	36	49	35	38	41	44	39.5	909
15	12:30	36	49	36	39	43	45	40.75	919.67
16	12:45	37	48	37	40	44	45	41.5	918.5
17	13:00	37	47	38	41	44	45	42	915.67
18	13:15	37	47	39	42	45	45	42.75	910.67
19	13:30	37	47	40	42	45	44	42.75	894.67
20	13:45	37	46	40	43	45	43	42.75	876
								Avg	796.101

Date:		**26/05/2019**							
Collector Type :		**ETC**							
Collector area:		**0.31m2**							
Tilt Angle:		**32**							
		Collector Temperatures		**Tank Temperatures**					
#	**Hour**	**T1:T_{in}**	**T2:T_{out}**	**T3**	**T4**	**T5**	**T6**	**$\bar{T}$tank**	**G_{global}(w/m2)**
1	09:00	32	45	27	31	36	37	32.75	535
2	09:15	27	44	27	31	37	35	32.5	603.5
3	09:30	27	43	28	32	37	36	33.25	645.33
4	09:45	28	42	29	33	37	35	33.5	695
5	10:00	29	40	29	33	37	34	33.25	741.67
6	10:15	29	41	29	33	37	34	33.25	784.33
7	10:30	30	55	30	34	37	35	34	821.5
8	10:45	30	53	30	34	37	36	34.25	850.67
9	11:00	31	56	31	34	37	37	34.75	883
10	11:15	32	59	31	35	37	38	35.25	909
11	11:30	32	60	32	35	38	39	36	931.33
12	11:45	33	62	32	35	38	41	36.5	957.5
13	12:00	34	65	33	36	39	44	38	970.67
14	12:15	34	62	33	36	39	43	37.75	975.67
15	12:30	34	48	35	37	42	47	40.25	980.33
16	12:45	35	47	37	39	44	47	41.75	979.33
17	13:00	35	46	38	41	47	47	43.25	975.67
18	13:15	36	45	39	44	48	45	44	929.5
19	13:30	36	44	39	44	48	43	43.5	753
20	13:45	37	46	41	45	48	44	44.5	961.33
								Avg:	844.17

Date:		**27/05/2019**							
Collector Type :		**ETC**							
Collector area:		**0.31m2**							
Tilt Angle:		**32**							
		Collector Temperatures		**Tank Temperatures**					
#	**Hour**	**T1:T_{in}**	**T2:T_{out}**	**T3**	**T4**	**T5**	**T6**	**$\bar{T}$tank**	**G_{global}(w/m2)**
1	09:00	23	38	25	27	28	32	28	519
2	09:15	26	39	24	26	27	31	27	550
3	09:30	27	39	25	26	28	32	27.75	626.67
4	09:45	28	40	25	27	29	33	28.5	684
5	10:00	28	41	26	28	31	35	30	717.67
6	10:15	29	43	27	29	32	35	30.75	756
7	10:30	30	43	28	30	34	37	32.25	792.33
8	10:45	30	44	28	31	35	37	32.75	830
9	11:00	31	43	29	32	36	37	33.5	828.67
10	11:15	32	46	31	34	38	40	35.75	902
11	11:30	33	47	32	36	40	41	37.25	935
12	11:45	34	47	34	37	41	42	38.5	960.33
13	12:00	34	46	35	39	42	42	39.5	918.33
14	12:15	33	43	36	39	43	42	40	457.67
15	12:30	34	44	37	40	43	42	40.5	948
16	12:45	35	45	38	41	44	41	41	902.33
17	13:00	36	45	39	42	44	42	41.75	762.33
18	13:15	37	45	40	43	45	42	42.5	731.67
19	13:30	37	43	40	42	44	40	41.5	461
20	13:45	38	41	41	43	45	41	42.5	935
								Avg	760.9

Date:			**20/06/2019**						
Collector Type :			**ETC**						
Collector area:			**0.31m2**						
Tilt Angle:			**32**						
		Collector Temperatures		**Tank Temperatures**					
#	**Hour**	**$T1:T_{in}$**	**$T2:T_{out}$**	**T3**	**T4**	**T5**	**T6**	**$\bar{T}tank$**	**G_{global}(w/m2)**
1	09:00	27	37	25	26	27	27	26.25	342.33
2	09:15	26	37	25	26	27	28	26.5	481.33
3	09:30	26	36	26	27	28	30	27.75	557
4	09:45	27	36	26	27	28	31	28	493
5	10:00	27	37	27	28	30	32	29.25	767
6	10:15	28	39	27	29	31	33	30	634.33
7	10:30	29	40	28	29	32	34	30.75	836.67
8	10:45	29	39	28	30	33	35	31.5	656.33
9	11:00	29	41	29	31	34	34	32	833.33
10	11:15	30	43	30	32	36	36	33.5	850
11	11:30	31	42	31	33	37	37	34.5	867.67
12	11:45	32	44	32	35	38	39	36	864.67
13	12:00	33	45	33	36	39	39	36.75	707.67
14	12:15	33	46	34	37	39	39	37.25	910
15	12:30	33	46	35	38	40	40	38.25	906.67
16	12:45	34	45	36	39	42	42	39.75	915.5
17	13:00	35	45	37	40	42	42	40.25	894
18	13:15	35	45	38	40	43	42	40.75	906
19	13:30	36	45	39	41	44	42	41.5	896
20	13:45	36	46	39	41	44	42	41.5	875.33
								Avg:	759.74

Date:		**23/06/2019**							
Collector Type :		**ETC**							
Collector area:		**0.31m2**							
Tilt Angle:		**32**							
		Collector Temperatures		**Tank Temperatures**					
#	**Hour**	**T1:T_{in}**	**T2:T_{out}**	**T3**	**T4**	**T5**	**T6**	**$\bar{T}$tank**	**G_{global}(w/m2)**
1	09:00	27	37	26	28	29	31	28.5	417
2	09:15	29	42	27	28	29	33	29.25	465.67
3	09:30	30	42	27	28	29	34	29.5	598.33
4	09:45	30	44	28	29	30	36	30.75	644.67
5	10:00	31	46	28	29	31	37	31.25	680.33
6	10:15	32	48	29	30	32	38	32.25	735
7	10:30	32	47	29	30	33	39	32.75	763.33
8	10:45	32	48	29	31	35	39	33.5	792.33
9	11:00	33	51	30	32	36	41	34.75	824
10	11:15	32	50	30	32	37	41	35	853
11	11:30	34	48	33	34	35	41	35.75	879
12	11:45	35	49	35	36	36	40	36.75	899.67
13	12:00	37	50	37	37	37	42	38.25	911
14	12:15	38	51	37	37	38	41	38.25	914
15	12:30	39	51	38	38	39	43	39.5	921
16	12:45	39	50	39	39	40	47	41.25	927.33
17	13:00	39	49	39	39	42	48	42	929
18	13:15	40	48	39	40	45	47	42.75	901
19	13:30	40	48	39	41	47	48	43.75	910.67
20	13:45	41	49	40	43	49	48	45	873.33
								Avg:	791.98

	22-5-2019	26-5-2019	27-5-2019	28-5-2019	29-5-2019	30-5-2019	06/10/2019	06/11/2019	17/6/2019	20/6/2019	23/6/2019	24/6/2019	25/6/2019	26/6/2019
	Ambient temperature / [°C]	Ambient temperature / [°C]	Ambient temperature / [°C]	Ambient temperature / [°C]	Ambient temperature / [°C]	Ambient temperature / [°C]	Ambient temperature / [°C]	Ambient temperature / [°C]	Ambient temperature / [°C]	Ambient temperature / [°C]	Ambient temperature / [°C]	Ambient temperature / [°C]	Ambient temperature / [°C]	Ambient temperature / [°C]
01:00 ص	25.709	16.473	15.109	17.009	20.355	26.991	20.373	22.7	21.673	19.518	19.791	19.782	20.691	23.582
02:00 ص	26.591	15.655	15.409	16.809	19.173	27.027	20.082	23.491	21.5	19.418	18.991	20.109	20.955	23.009
03:00 ص	25.091	15.145	14.864	16.227	19.027	26.082	20.273	23.482	21.555	18.873	18.909	20.055	20.855	22.418
04:00 ص	24.855	15.527	14.782	16.955	18.336	24.136	20.391	22.982	20.691	18.809	18.6	20.35	20.764	22.591
05:00 ص	24.091	14.755	14.455	17.518	18.373	25.736	20.018	23.427	20.191	18.936	18.536	20.209	20.164	23.055
06:00 ص	24.655	15.255	14.645	17.4	20.782	26.091	20.218	22.691	20	19.018	18.564	19.882	20.355	23
07:00 ص	27.609	16.455	18.164	18.064	23.509	29.727	23.736	25.191	20.936	20.17	20.236	20.427	22.1	25.573
08:00 ص	32.7	21.273	22.925	24.292	30.182	36.158	28.842	30.691	24.064	22.208	22.073	25.017	27.173	29.3
09:00 ص	37.518	24.858	26.027	23.927	32.673	36.664	29.191	33.142	24.633	23.809	23.655	26.755	30.409	30.327
10:00 ص	40.864	25.091	28.827	26.1	35.033	40.191	30.5	37.182	26.118	26.718	30.833	29.927	32.225	32.65
11:00 ص	42.008	25.864	28.742	29.125	38.664	42.867	31.575	36.327	27.408	28.258	30.8	31.592	32.673	35.082
12:00 م	42.036	30.455	32.036	30.455	35.573	44.527	32.7	34.642	29.291	30.491	30.245	34.5	35.3	34.991
01:00 م	40.427	31.675	30.127	31.582	35.417	43.718	32.518	36.118	29.008	31.527	33.791	35.218	35.85	35.133
02:00 م	38.95	29.845	30.364	33.333	35.582	45	33.108	34.5	28.982	30.992	35.633	34.592	37.355	35.718
03:00 م	37.073	28.7	29.891	32.573	35.655	43.136	33.336	35.5	29.073	30.727	33.082	34.055	34.091	34.436
04:00 م	35.636	28.417	29.025	31.673	34.483	42.8	32.409	34.1	28.033	31.064	32.1	33.673	32.717	34.492
05:00 م	36.591	24.891	29.891	30.564	32.818	36.236	31.736	34.618	27.6	28.918	29.825	32.45	32.473	32.882
06:00 م	34.973	24.882	28.255	29.917	33.527	36.727	30.827	33.5	26.373	27.7	28.718	30.964	30.709	31.636
07:00 م	32.083	21.555	24.742	26.164	32.064	34.225	29.825	31.364	25.375	26.3	27.018	29.127	28.367	29.975
08:00 م	28.709	19.508	21.118	22.118	28.95	30.518	26.836	27.973	22.655	23.645	23.8	25.175	26.218	26.9
09:00 م	28.809	18.036	18.991	20.336	28.145	29.336	25.464	26.318	21.318	22.025	21.936	23.633	24.773	25.191
10:00 م	28.9	17.282	17.409	19.267	28.045	28.509	24.718	25.567	21.083	21.345	21.1		23.958	24.282
11:00 م	29.691	16.1	16.991	19.009	27.064	28.2	23.783	24.445	20.564	20.727	21.317		24.264	23.167
12:00 ص	30.118	15.533	17.133	20.733	26.3	28.064	23.1	24.209	19.655	20.458	20.864		23.809	22.882

	22-5-2019	26-5-2019	27-5-2019	28-5-2019	29-5-2019	30-5-2019	06/10/2019	06/11/2019	17/6/2019	20/6/2019	23/6/2019	24/6/2019	25/6/2019	26/6/2019
	Solar irradiation[W/m^2]	Solar irradiation[W/m^2]	Solar irradiation[W/m^2]	Solar irradiation[W/m^2]	Solar irradiation[W/m^2]	Solar irradiation[W/m^2]	Solar irradiation[W/m^2]	Solar irradiation[W/m^2]	Solar irradiation[W/m^2]	Solar irradiation[W/m^2]	Solar irradiation[W	Solar irradiation[W/	Solar irradiation[W	Solar irradiation[W
08:00 ص	276	304.5	303.67	279	271.33	269.33	282	278	155.5	187.33	126	264	253.67	255
08:15 ص	321.33	356.33	360	333.67	328	331	350	325.33	284.67	199.5	198.33	332.5	308	310.67
08:30 ص	382	419	314.67	399	383.67	375.67	397	381.33	136	227.67	215.33	379	362.67	366
08:45 ص	428	477.67	468.67	445.67	448	431	453.67	436.33	228.33	396	237.67	435	429	427.5
09:00 ص	476	535	519	497.67	495	482	509.67	490	366.33	342.33	417	491	474.33	475.33
09:15 ص	531.67	603.5	550	549.67	548.67	534.33	565	539.67	301.67	481.33	465.67	545.33	524.67	530.67
09:30 ص	580.33	645.33	626.67	603.33	599	582.67	618.33	594.5	437	557	598.33	597.67	576	581
09:45 ص	631.33	695	684	649.67	650.67	634	674	634.33	622	493	644.67	649.5	624	631
10:00 ص	695.5	741.67	717.67	698	697	672.33	705.67	673.67	600.67	767	680.33	682.67	666.67	676.67
10:15 ص	722	784.33	756	729.33	743.5	716.33	750.67	727	785	634.33	735	720.67	712.5	725.5
10:30 ص	779.33	821.5	792.33	771	773	755.33	786.67	761.67	555	836.67	763.33	764.67	744.67	755.67
10:45 ص	799	850.67	830	803	807.33	790.33	822.33	800	480.33	656.33	792.33	790.33	779	794
11:00 ص	852.33	883	828.67	833.67	837.67	822.67	846.67	839	620	833.33	824	825.67	809.33	824.67
11:15 ص	868	909	902	861	862.33	853.5	883	856	570.33	850	853	851	834	852
11:30 ص	900.67	931.33	935	881.67	880.33	872.33	901	880.67	939	867.67	879	871	860.67	874
11:45 ص	908	957.5	960.33	895.67	899.5	888.33	919	900.33	657	864.67	899.67	889	878.67	895.5
12:00 م	909.33	970.67	918.33	915	907.33	902	927	910	1012	707.67	911	899.33	888.5	906.33
12:15 م	890.33	975.67	457.67	925.33	917.67	905.33	934	918.67	505	910	914	909	899.33	915.67
12:30 م	913	980.33	948	924.67	922	914.33	940	928	805.67	906.67	921	919.67	903.67	924.33
12:45 م	939	979.33	902.33	930	921.33	905.5	947	921.33	807	915.5	927.33	918.5	906.67	925.67
01:00 م	930.33	975.67	762.33	925.67	913	909	928.33	446	570.67	894	929	915.67	901	926.33
01:15 م	916.67	929.5	731.67	908.67	899.5	897.67	915.67	460	628	906	901	910.67	893.33	916
01:30 م	893.33	753	461	899.33	888.67	874.33	898.67	953.67	727	896	910.67	894.67	878	906
01:45 م	882.67	961.33	935	881.67	873	864	890.33	919.33	761	875.33	873.33	876	863.33	888.33
02:00 م	863	626.33	705.67	856	854	845.33	868.67	857	895.67	847	832	851.67	842.33	868
02:15 م	834.5	609.67	530.67	830	832	812.5	840	843.33	785.33	825.5	844.33	821.5	818	846.33
02:30 م	810.33	659.33	588	802	803	779	820.67	809.67	850.67	802.33	803.5	794	784.33	820.67
02:45 م	774.67	576	822	769.33	765	745.67	779.67	766	352.5	764	769	769	754	782
03:00 م	737.33	801.67	757.5	733.33	732.67	713.67	740.67	733.67	779.33	730.67	729.33	733.33	715.5	751.67

جامعة النجاح الوطنية

كلية الدراسات العليا

تحليل أداء أنظمة السخانات الشمسية المختلفة في الضفة الغربية

إعداد

لندا أحمد محمد منصور

إشراف

د. عماد بريك

د. عبد الرحيم أبو صفا

قدمت هذه الأطروحة استكمالاً لمتطلبات الحصول على درجة الماجستير في هندسة الطاقة النظيفة وترشيد الاستهلاك، بكلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس– فلسطين.

2019

تحليل أداء أنظمة السخانات الشمسية المختلفة في الضفة الغربية

إعداد

لندا أحمد محمد منصور

إشراف

د. عماد بريك

د. عبد الرحيم أبو صفا

الملخص

تبحث هذه الأطروحة بشكل تجريبي في أداء أنظمة السخانات الشمسية ذات المجمعات المسطحة والمجمعات ذات الأنابيب المفرغة، وهي الأكثر استخدامًا في فلسطين.

تم تركيب ثلاثة أنظمة من السخانات الشمسية المصنوعة محليا وهي: مجمِع مسطح ذو أنابيب ملتوية بمساحة 0.48 م^2 ومجمع مسطح ذو انابيب متوازية بمساحة 0.48 م^2 ومجمع ذو أنابيب مفرغة بمساحة 0.31 م^2 على سطح مبنى مركز أبحاث الطاقة في جامعة النجاح الوطنية. تم توصيل المجمعات الثلاثة بالتوازي مع خزان تخزين بسعة 30 لترًا.

تم التحكم في دورة المياه بين المجمعات وخزان التخزين بواسطة صمامات بحيث يتم اختبار مجمع واحد فقط في كل مرة.

كل 15 دقيقة، يتم جمع بيانات درجة حرارة مدخل المجمع ودرجة حرارة مخرج المجمع ودرجة حرارة الخزان عن طريق أجهزة استشعار درجة الحرارة. تم جمع بيانات الطقس (درجة الحرارة المحيطة والإشعاع الشمسي على سطح مائل) أيضا باستخدام محطة الطقس.

تم جمع البيانات لمدة 13 يومًا في شهري أيار وحزيران لعام 2019 (أربعة أيام للمجمع المسطح ذو الانابيب الملتوية وخمسة أيام للمجمع المسطح ذو الانابيب المتوازية وأربعة أيام للمجمع ذو الانابيب المفرغة) تمت دراسة أداء كل نظام على حدة. بعد ذلك، تم مقارنة أداء الثلاثة مجمعات خلال ثلاثة أيام لها نفس الظروف الجوية.

أظهرت النتائج أن الطاقة اليومية التي جمعها المجمع المسطح ذو الانابيب الملتوية هي 1015 واط ساعة/ م ^{2} و1415 واط ساعة/ م^2 للمجمع المسطح ذو انابيب متوازية و1854 واط ساعة/ م^2

للمجمع ذو الانابيب المفرغة بينما كانت كفاءة الأنظمة 26% و38% و49% للمجمِع للمسطح ذو أنابيب ملتوية والمجمع المسطح ذو انابيب المتوازية والمجمع ذو الأنابيب مفرغة على التوالي.

يظهر التحليل الاقتصادي أن جميع أنظمة السخانات الشمسية مجدية اقتصاديًا حيث كان صافي القيمة الحالية وزمن استرجاع رأس المال على التوالي للأنظمة الثلاثة كالاتي: 17660 شيكل، 1.56 سنة للمجمع المسطح ذو الانابيب الملتوية و 18400 شيكل و1.5 سنة للمجمع المسطح ذو انابيب المتوازية و10400 شيكل و5.35 سنة للمجمع ذو الأنابيب مفرغة.