Energy Performance and Economic Feasibility Comparison of Evacuated Tube and Flat Plate Solar Collectors for Domestic Water Heating

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ABSTRACT

The study provides performance analysis and economic feasibility examination of Solar Domestic Water Heating (SDWH) Systems employing two different types of solar collectors, Flat Plate Collector (FPC) and Evacuated Tube Collector (ETC). The work studies the system performance, solar system fraction, collector and storage tank outlet temperatures, collected energy, and the system efficiency.

The performance analysis of the two solar water heating systems was carried out considering the annual weather conditions of Beirut city by using T*SOL® and TRNSYS Simulation tools. Results showed that the annual efficiency of SDWH using ETC (44%) was 4 points more than the annual efficiency of SDWH employing FPC (40%). The annual solar fraction of SDWH with ETC (89%) is found to be 9 points more than that of FPC (80%). This makes the system with ETC more effective in terms of energy performance, leading to more economic benefits over its life of the operation. This has been proved by evaluating both systems' economic feasibilities over their operation life (20 years). The economic feasibility results showed that the total savings of SDWH using ETC is $ 47,615, and the saving-to-investment ratio is 7.7. The total savings of the system using FPC is $ 42,840, and saving-to-investment ratio is 7.

Keywords: Solar domestic water heating, solar collectors, Flat plat collector, Evacuated tube collector, Performance analysis, Economic feasibility.

ÖZ

Bu çalışma kullanım suyu ısıtılmasında yararlanılan iki farklı güneş toplayıcı düzeneğini karşılaştırmalı olarak incelemeyi amaçlamaktadır. Çalışma düz plakalı ve vakum tüplü güneş toplayıcı düzeneklerinin performansını ve ekonomik fizibilitesini ortaya koymaktadır. Dikkate alınan göstergeler toplanan enerji, güneş enerjisi katkı oranı, düzenek performansı ve verimi ile toplayıcı ve depo çıkış sıcaklıklarıdır.

Düzeneklerin performans karşılaştırması Beyrut hava koşulları dikkate alınarak TRNSYS ve T*SOL yazılımları ile oluşturulan modellerin simülasyon sonuçlarının tetkiki ile gerçekleştirilmiştir. Sonuçlar vakum tüplü toplayıcının yıllık veriminin (% 44) düz plakalı toplayıcının yıllık veriminden (% 40) 4 puan daha yüksek olduğunu göstermektedir. Bunun yanında vakum tüplü toplayıcının yıllık güneş enerjisi katkı oranının (% 89) düz plakalı toplayıcının güneş enerjisi katkı oranından (% 80) 9 puan daha fazla olduğu ortaya çıkarılmıştır. Bu durum vakum tüplü güneş toplayıcı düzeneğin enerji performansının daha iyi olduğunu göstermekte ve çalışma süreci boyunca daha fazla ekonomik fayda sağlayacağı sonucunu doğurmaktadır. Yapılan ekonomik fizibilite çalışmasının sonucu da bunu göstermektedir. Yapılan çalışmada vakum tüplü güneş toplayıcısının kullanım suyu ısıtılmasında faydalanılması ile yirmi yıllık çalışma süresi boyunca Beyrut koşullarında toplam 47,615 $ tasarruf edileceği ve tasarruf-yatırım oranının ise 7.7 olacağı hesaplanmıştır. Düz plakalı güneş toplayıcısının kullanılması durumunda ise toplam tasarrufların 42,840 $, tasarruf-yatırım oranının ise 7 olacağı bulunmuştur.

Anahtar Kelimeler: Güneş enerjisi ile kullanım suyu ısıtılması, Güneş toplayıcıları, Vakum tüplü güneş toplayıcısı, Düz plakalı güneş toplayıcısı, Performans analizi, Ekonomik fizibilite

DEDICATION

This thesis I would like to dedicate to my friends and family. I have a unique feeling of appreciation to my loving parents, Najib and Dania, whose words of encouragement echo in my ears. Ahmad, my brother, who has never left my side and is very special.

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It gives me great pleasure to thank my father and mother, who worked hard and watched over my upbringing and education since childhood. I thank everyone who contributed to my learning journey, from school teachers and university doctors that have all the credit for teaching me until I became a Mechanical Engineer.

I also offer my full appreciation and thanks to my professors and my wonderful supervisor, Assoc. Prof. Dr. Murat Özdenefe for all the support in my successful research, by which I ask God to add value to this science. Also, a special thanks to the Eastern Mediterranean University administration for providing the students with the required services, and help in all matters, to seek knowledge in a comfortable space.

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INTRODUCTION

1.1 Background

The race for modern technological development has led to an evolution of society and the economy. The growing energy requirement per capita due to an increasingly demanding lifestyle and the high consumption of non-renewable sources of energy such as fossil fuels led man to seek new sources of energy that must have the characteristic of being renewable over a life cycle.

Renewable energy sources will be the future of energy itself. They will focus on innovations that will lead to the optimal and rational use of these resources to ensure people's current and future needs. (Timmons, 2014).

One of the most important renewable energy sources is Sun energy, which solar collector systems of various types can absorb to heat water for domestic and industrial use. Solar heating systems are eco-friendly systems that can work with zero carbon emissions as independent systems or hybrid systems using auxiliary heaters (electric or gas).

1.2 Motivation

Lebanon is a developing country that faces persistent economic and infrastructural problems. Since the civil war ended in 1994, the electric crisis remains one of the challenging issues the country faces. The country's national grid can supply only half of the electricity demand. This issue Force people to find alternative sources, avoiding relying entirely on the national grid as their primary source of energy to supply their houses with power. Lebanese switch to private power generators to provide their homes with electricity when blackouts hit, and usually, it hits every day (Whewell, 2019).

Private power generator bills have always been very expensive and do not supply enough power to run water heating systems. This problem makes a huge problem for Lebanese people over the year, especially during the fall, winter, and spring seasons. This made Lebanese install solar water heating systems as an alternative that relies mainly on Sun's energy.

However, the big question for the people who want to install such systems is which type of collectors is more efficient under the Lebanese weather conditions (typical Mediterranean climate) and whether installing such systems is economically feasible and worth the investment.

1.3 Thesis Objectives

This research thermal analysis of two different domestic solar water heating systems −Flat Plate Collector (FPC) and Evacuated Tube Collector (ETC) − will be performed. It is intended to investigate their performance under typical Mediterranean Climate Beirut weather conditions. The collector outlet temperature, storage tank outlet temperatures, system efficiency, system solar fraction, the energy accumulated and collected in the tank and collector are some of the detailed examination parameters.

The parameters mentioned above will be evaluated (via simulations) for both systems working under Beirut city weather conditions.

The work's final stage involves economic feasibility calculations for both systems and shall propose the most feasible one for hot water production.

1.4 Thesis Organization

The organization of this thesis consists of the following:

Chapter 2, presents the literature review regarding the importance of renewable energy in solving energy supply issues, the importance of the Sun as a source of energy, the definition of solar water heating systems, and their types for domestic hot water heating system performance.

Chapter 3, presents mathematical model equations of the SDWH system.

Chapter 4, involves a detailed explanation of the methodology followed in this work. It thoroughly describes the models generated by TRNSYS and T*SOL simulation tools employed for studying and comparing the performance of the two solar heating systems with different types of collectors: Evacuated tube and flat plate collectors.

Chapter 5, is about the analysis of the simulation outcomes. Two systems' performances are scrutinized and compared in this chapter. The results presented in this chapter lays the foundations of the economic analysis.

Chapter 6, presents the economic feasibility results, and lastly, Chapter 7 summarizes the conclusions drawn from this work.

Chapter 2

LITERATURE REVIEW

2.1 Background

The world is experiencing significant changes in energy sources that control the joints of daily human life. There is no doubt that the three types of fossil-based energy sources- coal, oil, and gas, which account for more than 85% of the world energy production are the most widely available sources today. However, they are currently facing challenges summarized in an agreement, the Paris Agreement. The agreement calls for reducing coal, oil, and gas use in energy production and replacing it with renewable energy production. Renewable energy reduces the number of air pollution and maintains a clean and healthy environment. (Gray, 2017) .

In 1760, the early development of solar water heaters was by the Swiss naturalist scientist Horace de Saussure; he built a simple collector system made up of a wooden box painted in black covered by glass. His solar collector invention reached a maximum temperature of 70 °C in optimal weather conditions. The drawback of his design was that it losses lots of heat and was not very effective. In 1891, Clarence M. Kemp created the first commercial solar water heating system with an improved ability to maintain heat which made his system commercially viable on a wide scale for the first time. In 1909 William Bailey created a more ergonomic compact design and became a market leader in solar thermal energy. His system was the first system to place the tank on the roof and the collector underneath. Bailey system was the first practical system to supply hot water at night after being stored in the daytime (Sunpad, 2019).

Solar water heating systems used today helps in creating new job opportunities in terms of manufacturing and installation. Alternative energy projects provide jobs for manufacturing, installation, maintenance operations, transportation, logistics, financial services, legal, consulting, and others. This helps create positive economic impacts and fluctuations in the prices of fossil fuels and natural gas (EEA, 29 Nov 2012).

2.2 Issues of Energy Supply, Peak Oil and, Depletion of Resources

Power production and heating (space, process, water) globally originates primarily from fossil fuels. Suppose the use of fossil-fuels remains high, as shown in figure 1. In that case, all supplies of fossil fuels will be exhausted, even if new large fossil-fuel reserves were founded. 'The Peak of oil' indicates the point of time at which the maximum-rate worldwide exploitation of petroleum is achieved. Many experts assume that 'peak oil' is expected to take place in a decade and cause the world economy to experience big-scale disruptions. Others believe that new previously uneconomic reserves will be utilized as the cost of oil rises. There are also small resources of uranium for running nuclear power plants. The new nuclear power plants may take a long time to construct because of strict safety and planning regulations (Aleklett et al., 2010).

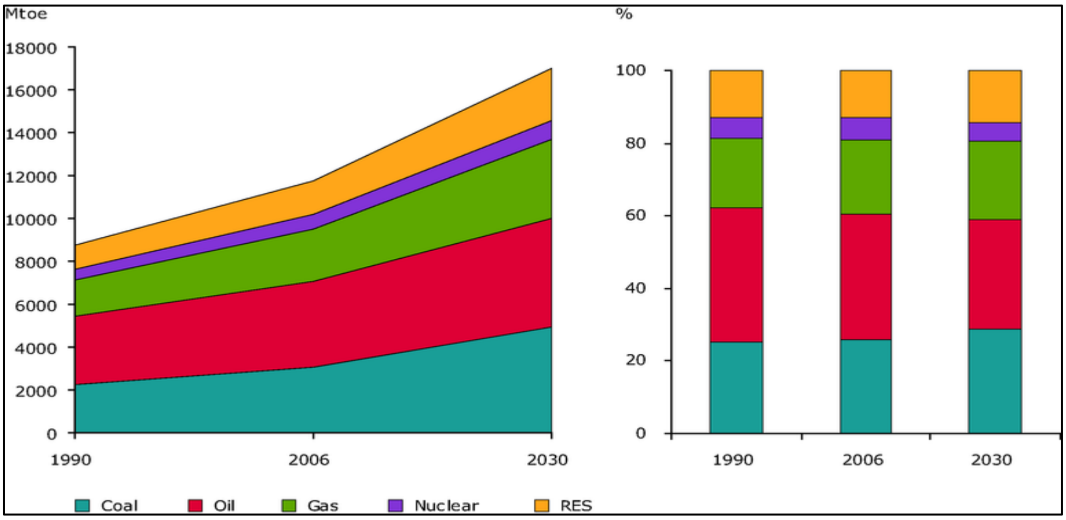

Figure 1: Total Global Consumption of Primary Energy by Fuel (EEA, 29 Nov 2012).

The future of short-run developments in energy prices is unclear. Energy costs have traditionally adjusted to track oil prices, which the economic growth and global conflicts have highly influenced. Crude oil prices increased in 2009 to price of $100/ barrel, (a barrel contains approximately 160 Liters of crude oil), then had a dramatic fall of $40 per barrel within a world economic decline as shown in figure 2 (Amadeo, 2020).

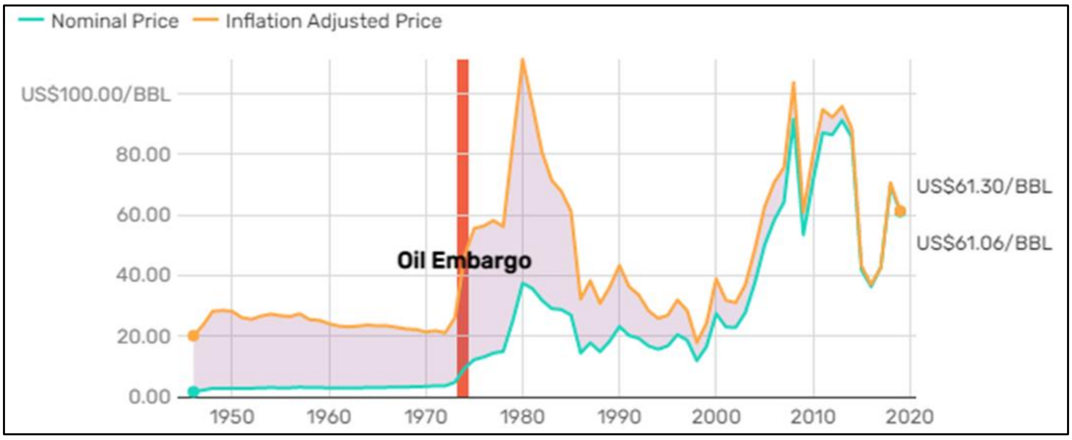

Figure 2: OPEC Crude Oil Price Per Barrel Since 1946 (Amadeo, 2020)

2.3 CO_2 Emissions and Climate Change

Excessive greenhouse gas emissions, such as carbon dioxide, nitrous dioxide, chlorofluorocarbons, methane, ozone, and water vapor, cause an increase in global mean temperature, which causes melting of the ice cap, extreme weather conditions, and increases in sea level. There is a need to reduce the generated emission of carbon dioxide significantly. One of the simplest and most efficient ways of doing this is to substitute the petroleum sources used for heating water with solar energy.

In developed countries, domestic hot water generation accounts for about 5% of total fuel usage. It constitutes more than 10 % in terms of electricity supplied to homes. The best cost-effective way to minimize carbon emission for several households in colder climates is to reduce space heating demands first before installing solar hot water. The very first goals here are the modernization of insulated and more efficient boilers. When these changes are done, the next largest energy-saving initiative becomes solar water heating (Laughton, 2010).

2.4 Solar Water Heating: A Renewable Technology

The wellspring of life on earth is the Sun energy. As sunlight strikes the earth's surface, it absorbs some of the sunlight and heats the surface. This energy could increase the water temperature used for cleaning, cooking, and other procedures such as swimming-pools, residential, and workspaces. Solar energy usually varies along the season and is not always consistent because of daily changing weather patterns. However, when the Sun is not shining, solar energy previously collected and stored can be used.

Solar collectors are commonly located on building roofs and could also be connected or located on the ground or vertical surfaces of walls and window frames. Solar collectors typically are set to fixed orientation, preferably South (in the northern hemisphere). Yet could similarly be placed on spinning trailing technology to track the Sun path through the sky.

2.5 What Solar Domestic Water Heating (SDWH) Technology Can Achieve?

SDWH will contribute enormously to the domestic hot water supply for houses and workplaces. Most SDWH devices can collect anywhere between 30% to 90% of average yearly water heating energy. We should expect 90 to 100% of the hot water demands to be supplied in summer. (Yaciuk, 1981)

Some crucial advantages of the DWH systems are listed below:

- Solar heaters provide a very high degree of safety that is not available in other water heating products such as gas heaters and electric heaters, thus avoiding fire risk
- Solar heaters are distinguished by their high ability to absorb and store heat.
- It is characterized by the ease of installation and maintenance
- Solar heaters come with various storage capacities, making them a suitable solution for all purposes, whether in the home, office buildings, hotels, etc.
- It provides hot water and generally does not require electricity. It involves an emergency electrical system that works in the absence of the Sun
- It has a long service life.

2.6 Types of Solar Collectors

Solar thermal collectors have various types categorized as low, medium or high-temperature collectors.

2.6.1 Flat Plate Solar Collectors (Low Temperature)

This type is the most common thermal collector used everywhere. The flat plate performs as a receiver that collects energy from the Sun and heats the absorber plate. Converted energy into the form of heat is then transferred to the fluid. These collectors have a series of copper tubes above or under the absorber plate, which, when exposed to the Sun, absorb solar radiation and transmit to the fluid that passes through them.

Flat plate solar collectors are used to produce domestic hot water, swimming pool heating, and space heating usage. The collector is located in an insulated rectangular box, whose standard dimensions are between 80 and 120cm wide, 150 and 200cm high, and 5 and 10cm thick (although there are models bigger). (Hess, 2016).

Flat plate collectors are made up of five main elements, as shown in figure 3:

i. The transparent cover (glazing sheet from glass or similar materials).
ii. The absorber (Pickup) plate (black surface that will absorb sunlight).
iii. Insulation.
iv. The casing (container of all the above).
v. Pipes to carry fluid.

Transparent cover: It is responsible for letting solar radiation to pass, preventing back emission of heat by the pickup plate from the system, and reduce losses due to convection. The greenhouse effect is currently being achieved with a glass or plastic cover, increasing the collector heat absorption efficiency.

Pickup plate: Its mission is to absorb radiation in the most efficient way possible and transform it into usable thermal energy by transferring it to the heat transfer fluid (water, oil, air, etc.).

Insulator: The collector plate is insulated on its back and sides, preventing thermal losses to the outside. The characteristics of these insulators are:

- Resist high temperatures, which are often achieved by placing a reflective layer between the plate and the insulation, prevent the insulation from directly receiving radiation.
- Doesn’t degrade by ageing or other phenomena at working temperatures.
- Withstand the humidity that may occur inside the panels without losing its insulating quality.

Case: It is in charge of protecting and supporting the other elements that constitute the solar collector.

The case must have the following requirements:

- Ridged, it must withstand high sun temperatures and the pressure of the wind.
- Made of materials with good resistance to corrosion
- Provide enough ventilation for the inside of the collector to prevent water from condensing inside the collector
- Avoids the accumulation of rainwater, ice, or snow on the collector.

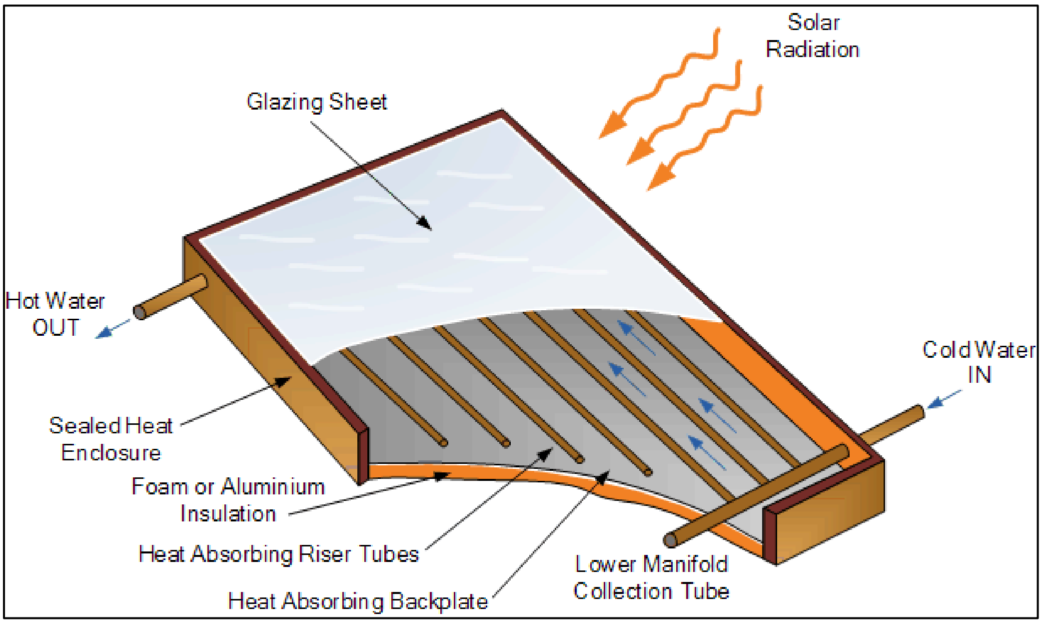

Figure 3: Flat Plate Solar Collectors ("Solar Flat Plate Collectors ", 2010)

2.6.2 Evacuated Tube Solar Collectors (Low Temperature)

Evacuated tube solar collector comes in two types depending on the system used for heat exchange between the plate and the heat carrier fluid; the two types of vacuum collectors are:

- With heat pipe
- Direct flow

With heat pipe (figure 4):

In this system, the vacuum tubes carry a vaporizing fluid that does not come outside the tube, and it works as a heat carrier. This fluid evaporates due to solar radiation. It rises to the upper end of the tube at a lower temperature; this causes the vapor to condense, give up its energy, and return to its liquid state. The condensed liquid falls by gravity to the bottom of the tube, where it again receives the heat of radiation, returns to vapor, and a new cycle begins. Heat pipes are considered superconductors of heat due to their low heat storage capacity and exceptional conductivity. The use of heat pipe is widespread in the industry and, based on this working principle, current vacuum manifolds are manufactured with a heat pipe. An advantage of the heat pipe system over the direct flow system is the dry connection between absorber and header, making it more accessible in installation and also means that the tubes can be changed without emptying the fluid throughout the system. This collector's drawback is that they must be mounted with a minimum angle of inclination of about 25 ° to allow the internal heat fluid to return to the heat absorption zone instead of the direct flow. (Sabiha, Saidur, Mekhilef, & Mahian, 2015).

Thanks to the vacuum insulating properties, the heat losses are reduced, and temperatures in the range of 77 to 177 ºC can be reached. Due to their cylindrical shape, they take advantage of radiation more effectively than flat plate collectors by allowing the sun rays to strike the tubes perpendicularly for most of the day. These collectors are more efficient than flat plate collectors. (Alghoul, Azmi, & Wahab, 2005).

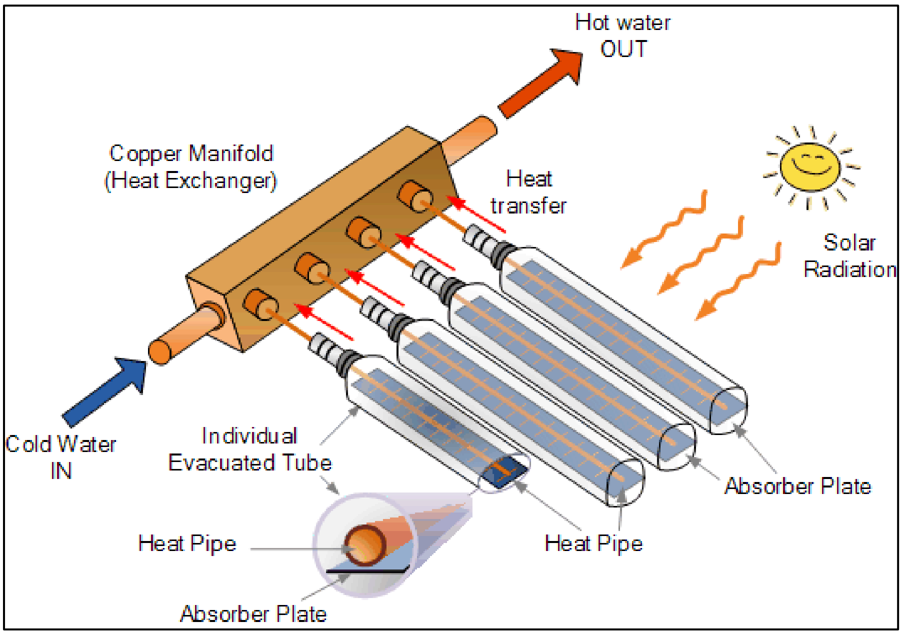

Figure 4: Evacuated Tube Collector with Heat Pipe ("Evacauted Tube Collector," 2010)

Direct flow (figure 5):

It consists of a glass tube group with an absorbent aluminum fin inside, connected to a metal tube (generally copper) or glass tube. The fin has a selective coating that absorbs solar radiation and prevents heat loss due to radiation. The heat transfer fluid circulates through the fluid tubes, where one of these tubes is for the inlet, and the other is the outlet.

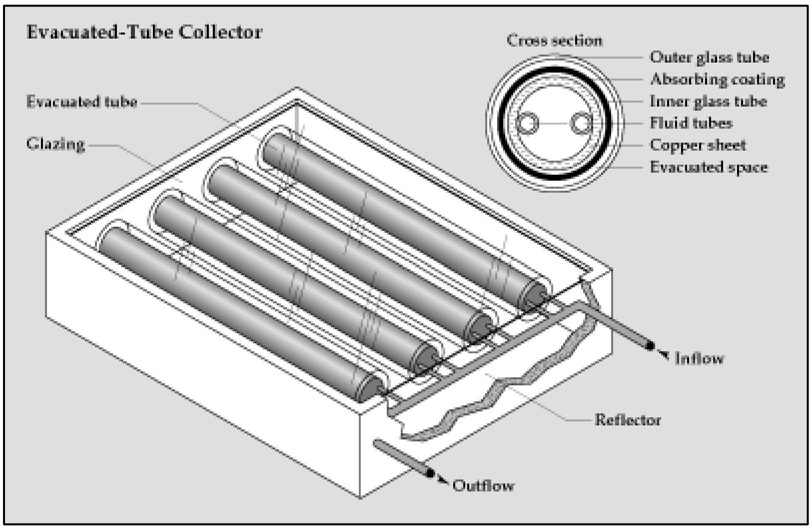

Figure 5: Direct Flow Evacuated Tube Collector (Alghoul et al., 2005)

2.6.3 Cylinder-Parabolic solar collector (High Temperature)

An essential feature of these collectors is achieving temperatures up to 400 ºC. Their applications are in both electric power generation and water heating. These collectors are constructed by folding a reflective sheet metal into a parabolic shape. A metallic black-colored tube, covered with a glass tube to reduce heat losses, is placed along the focal receiver line (figure 6).

The parabolic collector is oriented towards the Sun; the parallel rays incident on the collector is reflected towards the linear focus. Here the parabolic reflector acts as a concentrator, and therefore it requires to track the Sun during the day. For parabolic concentrators, one axis of tracking is enough for efficient operations. This type of collectors is generally arranged as groups in series connections. (Bellos, Daniil, & Tzivanidis, 2018).

Figure 6: Cylinder-Parabolic Solar Collector

2.6.4 Central Receiver System (High Temperature)

The heliostats (flat mirrors) in the central tower field (figure 7) reflect the solar radiation to a receiver installed at the top of a tower from which molten nitrate salts are circulated. These heats carried away by the heated salts produce steam in a boiler for power production in a Rankine cycle. The temperatures achieved in the tower may be 565 ^{o}C or higher.

When the heat energy collected is more than that is required for steam generation, excess heat is transferred to a hot tank capable of storing the heat for use in periods of low solar radiation or nights. It is necessary to have several flat (or curved) reflecting mirrors arranged in a field with solar tracking to change the mirrors' orientation following the sun location change to obtain high energy levels at high temperatures from solar energy. (Alarcon Villamil, Hortúa, & Lopez, 2013).


Figure 7: Central Receiver System ("Solar tower Mojave Desert, California," 2009)

Chapter 3

MATHEMATICAL MODEL EQUATIONS

3.1 Background

This work employs two different simulation tools -TRNSYS and T*SOL for modeling and simulating the thermal performance of Solar Domestic Water Heaters (SDWH) with Evacuated Tube Collectors ETC and Flat Plat Collectors. In this chapter, mathematical model equations of the SDWH system are presented. The equations given in this chapter are an integral part of the tools and are utilized during simulation runs for performance evaluations. The framework and main components of the SDWH system modeled by the tools are given in figure 8.

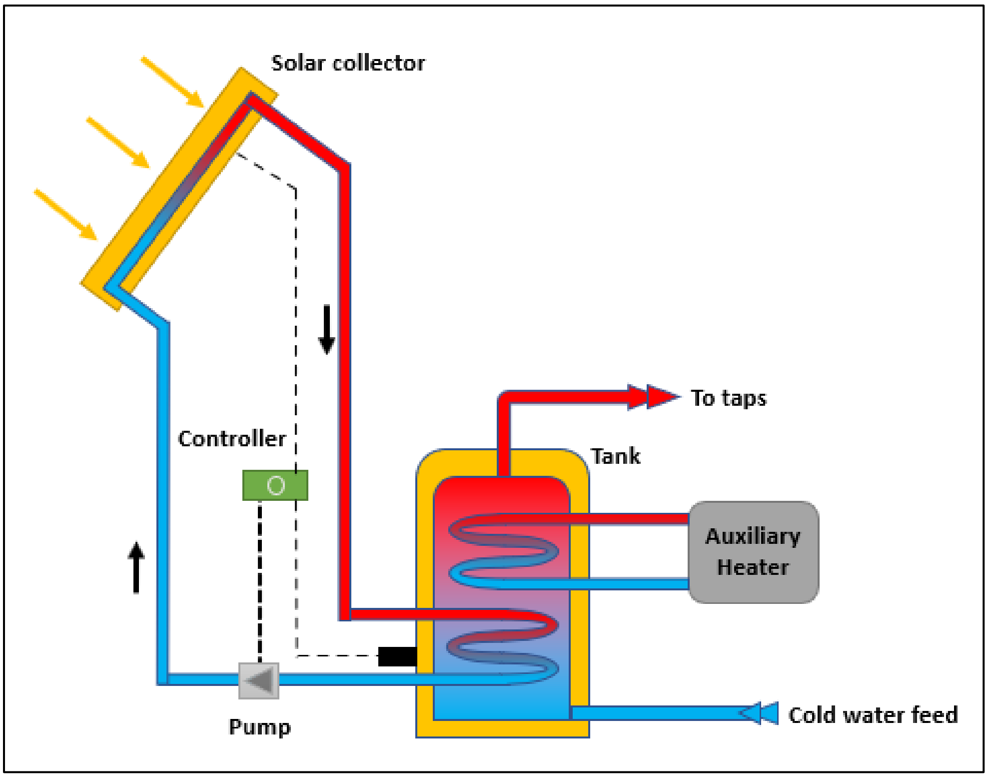

Figure 8: SDWH System Diagram

3.2 Model Equation of the SDWH System

The major component of the SDWH device is the collector that transforms solar energy into heat and transfer it to the storage tank through pipes and heat exchanger systems. The hot water storage tank helps compensate for the variations in energy supply and demand at various times throughout the day. In the case of inadequate solar energy, the auxiliary heating system provides the balance of energy to cover the requirements.

3.2.1 Collector Gains & Efficiency

The solar collector role in the SDWH is to absorb heat from the sunlight radiation. To convert it into thermal energy. Obtained thermal energy is collector gains and calculated by the following equation:

$$Q_{u-Collector} = \dot{m}_s c_p (T_2 - T_1) \tag{1.0}$$

The collector efficiency represents the ratio between the heat absorbed by the solar collector and the incident solar radiation on the active collector area, defined as follows:

$$\eta = \frac{Q_{u-collector}}{I * A_{Coll}} \tag{1.1}$$

- $Q_{U-Collector}$ = Useful energy gains [kWh]
- $\dot{m}_s$ = Mass flow rate of the water in collector [kg]
- C_p = Specific heat of water [4.19 kJ/kg K]
- T_1 and T_2 = Collector water inlet and outlet temperature difference [º C]
- I = Level of irradiance on the collector [W .m^-2]
- A_{Coll} = Collector area for FPC, ETC.

3.2.2 Pump Power, Efficiency and Heat Gains

The pump role is to circulate the fluid carrying the heat gains from the collector to the tank heat loop to exchange its heat with the water available in the tank. The pump is controlled by the system controller, as shown in figure 8.

The overall efficiency of the pump (mechanical) and the efficiency of the pump motor (electrical) are used to calculate the pumping efficiency, as shown in the following equation:

$$\eta_{Pumping} = \frac{\eta_{Overall}}{\eta_{Motor}} \tag{1.2}$$

- $\eta_{Pumping}$: Pumping efficiency
- $\eta_{Overall}$: Overall pump efficiency: motor efficiency * pumping efficiency
- η_{Motor}: Pump motor efficiency.

The power available at the pump shaft [kJ/hr] is calculated by:

$$P_{shaft} = P_{rated} * \eta_{motor} \tag{1.3}$$

- P_{shaft}: Shaft power required by the pumping process [kJ/hr].
- P_{rated}: Rated power of the pump [kJ/hr].

The energy transformed from the pump motor to the fluid stream [kJ/hr] is calculated as:

$$Q_{fluid} = P_{shaft}\left(1 - \eta_{Pumping}\right) + (P - P_{shaft})f_{motorloss} \tag{1.4}$$

- P: Power drawn by the pump at the current time [kJ/hr].
- $f_{motorloss}$: Fraction of pump inefficiencies that contribute to a temperature rise.
- $\eta_{Pumping}$: pumping process efficiency.

Energy transferred from the pump motor to the ambient [kj/hr] is given by:

$$Q_{ambient} = P_{rated}(1 - \eta_{motor})(1 - f_{motorloss}) \tag{1.5}$$

The temperature of the fluid [º C] at the exit of the pump is calculated as:

$$T_{fluid.out} = T_{fluid.in} + \frac{Q_{fluid}}{\dot{m}_{fluid}} \tag{1.6}$$

- Q_{fluid}: The energy that passes through the pump is transferred from the pump motor to the fluid stream. [kJ/hr].
- $\dot{m}_{fluid}$: Mass fluid flow rate going through the pump [kJ/hr].
- $T_{fluid.in}$: Temperature of fluid entering the pump [º C].

(The Solar Energy Laboratory, 2017)

3.2.3 Outlet Pipe Loses

The pipe used to transfer the heated fluid from the collector to the storage tank losses some of its energy to the surrounding environment. Heat loss from pipes depends on fluid temperature, as well as the outdoor ambient temperature. Figure 9 illustrates the pipe heat losses and how it is calculated.

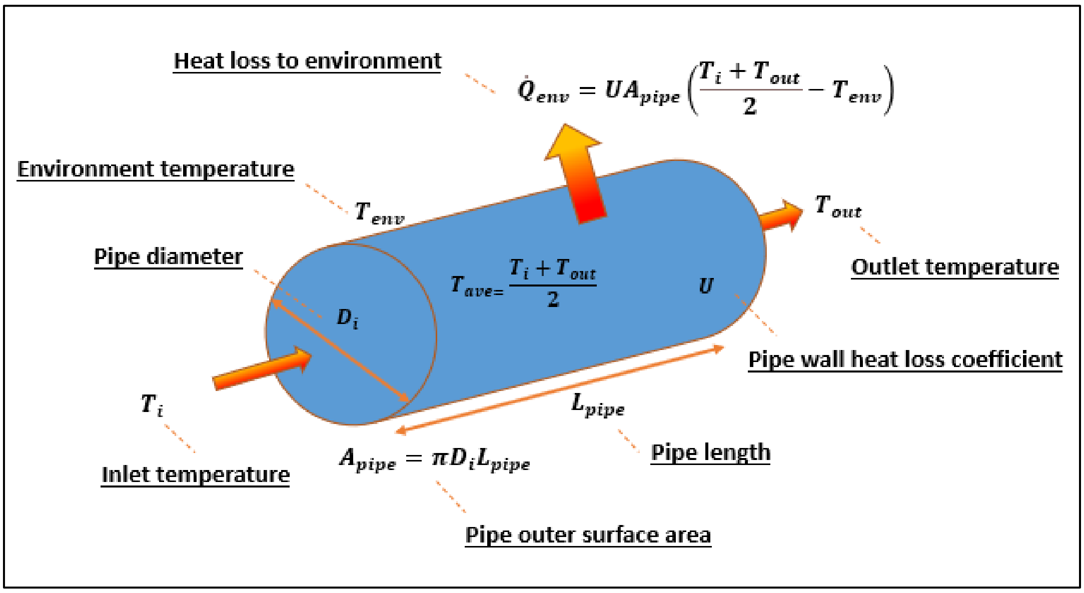

Figure 9: Pipe Heat Loss Diagram

The overall heat transfer coefficient (U) for the pipe is:

$$U = \frac{1}{\frac{1}{h_{int}}+\frac{D_i}{2k_{insul}}ln\frac{D_0}{D_{\text{i}}}+\frac{D_i}{D_0 h_{ext}}} \tag{1.7}$$

- U: overall heat transfer coefficient [W/m^-2. K]
- D_i: Inner diameter [m]
- D_0: Outer diameter [m]
- k_{insul}: Insulation Thermal Conductivity [W/m. K]
- h_{int}: Internal surface Heat Transfer Coefficient [W/m^2.K]
- h_{ext}: External surface Heat Transfer Coefficient [W/m^2.K].

(The Solar Energy Laboratory, 2017)

3.2.4 Hot Storage Tank Losses, Auxiliary Heating Gains & Energy Balance

The hot storage tank is a water tank used for storing hot water for domestic use. The tank volume is divided into ‘N’ equal horizontal layers (nodes) as shown in figure 10, and each node is presumed isothermal. The first node is at the top of the tank, and the final node is at the bottom. The thermal energy within the storage tank can be transferred through and out of each consecutive node; each node has thermal losses to the environment through conductivity. This thermal loss [kJ/hr] to the ambient is calculated as follows:

$$\dot{Q}_{loss.j} = U_{tank} \, . \, A_{top.j} \, . \left(T_j - T_{amb}\right) + U_{tank} \, . A_{bottom.j} \, . \left(T_j - T_{amb}\right) \, +$$
$$U_{tank} \, . \, A_{edge.j} \, . (T_j - T_{amb}) \tag{1.8}$$

- U_{tank}: Overall loss coefficient of the tank, per unit surface area of the tank [kJ/hr-m2-K]
- $A_{top.j}$: Surface area of the top of node j in contact with the top of the tank; = πD2/4 if j = 1, = 0 for all other nodes [m2]
- T_j: Temperature of the j_{th} node of the tank [°C]

- T_{amb}: Ambient (air) temperature; the environment temperature surrounding the tank [°C]
- $A_{bottom.j}$: Surface area of the bottom of node j in contact with the bottom of the tank; = $\pi D2/4$ if j = Nodes, = 0 for all other nodes [m2]
- $A_{edge.j}$: Surface area of the edge of node j in contact with the wall of the tank [m2].

Heat transfer through a node due to mass flow through the node is calculated as follows:

$$\dot{Q}_{massflow.j} = \dot{m} \,.\, c_p \,.\, (T_{j+1} - T_j) \tag{1.9}$$

- $\dot{m}$: Flow rate of fluid through the tank [kg/hr]
- c_p: Specific heat of tank fluid [kJ/kg-K]
- T_j: Temperature of the j_{th} node of the tank [°C]. where T_{j+1} = Tinlet if j = Nodes (the bottom of the tank).

Conduction between adjacent tank nodes is calculated as follows:

$$\dot{Q}_{cond.j} = \frac{k}{L_{cond}} \,.\, \frac{V_{tank}}{h_{tank}}\left(T_{j-1} - T_j\right) - \frac{k}{L_{cond}} \,.\, \frac{V_{tank}}{h_{tank}}(T_j - T_{j+1}) \tag{1.10}$$

- L_{cond}: Length of conduction between one node and the node adjacent above or below; the height of the tank divided by the number of nodes in the tank[m].
- k: Conductivity of tank fluid [kJ/hr-m-K]
- V_{tank}: Volume of the storage tank [m3]
- h_{tank}: Height of the tank [m].

Heat addition through an auxiliary heater [kJ/hr] is calculated as follows:

$$\dot{Q}_{aux.j} = I_{aux} \,.\, \dot{Q}_{aux,rated} \,.\, \eta_{aux} \tag{1.11}$$

- I_{aux}: The control signal of the auxiliary heater; changes to zero if the water temperature is above the setpoint, changes one if the water temperature in the tank is at or below the setpoint.
- $\dot{Q}_{aux,rated}$: Rated capacity (power) of the auxiliary heater [kJ/hr].
- η_{aux}: The efficiency of the auxiliary heater.

Auxiliary heat is the only input to the bottommost node of the heater.

Solving the temperature of the tank nodes, the energy balance over each fluid node is as follows:

$$\rho c_\rho V_j \frac{dT_j}{dt} = \dot{Q}_{massflow.j} - \dot{Q}_{loss.j} + \dot{Q}_{aux.j} + \dot{Q}_{cond.j} \qquad (1.12)$$

(The Solar Energy Laboratory, 2017)

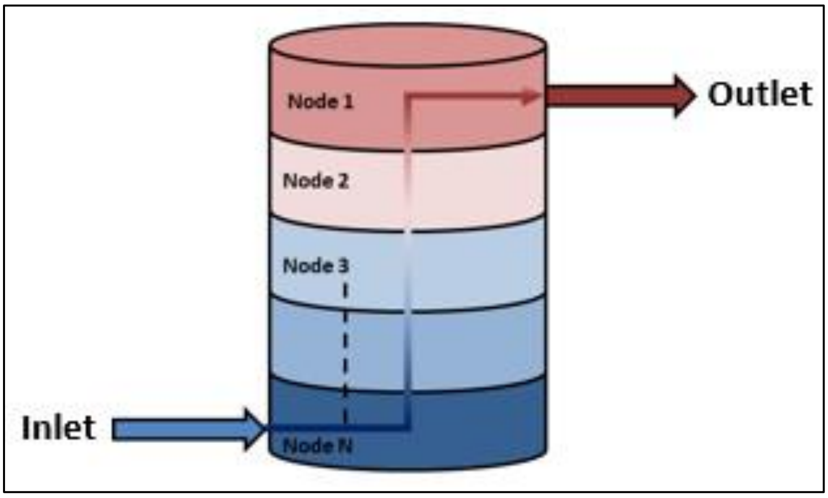

Figure 10: The Tank Volume Divided into 'N' Equal Nodes

3.2.5 Load Heat Energy Losses

After heat gained by the collector is stored hot water tank; this utilized energy by the consumer is considered as losses and calculated as:

$$\mathrm{Q_L} = m_L\, \mathrm{C_p}(\mathrm{T_O} - \mathrm{T_L}) \qquad (1.13)$$

- Q_L : Load heat energy [kJ]
- m_L : Mass of water consumption
- C_p : Specific heat of water [4.19 kJ/kg K]
- T_O : Mean Outside temperature in winter season [° C]
- T_L : Desired load temperature [° C].

3.2.6 SDWH Energy Balance

After demonstrating the calculation of the energy gains and losses of the SDWH system. The energy balance of the SDWH is calculated, as shown in figure 11 using the following equation:

Energy balance = (+Collector gain + Auxiliary gain + Pump gain - Energy to load – Tank loss – Pipe loss - Internal energy change). (1.14)

- Gains:

QCOLL = +Collector gain

QAUX = + Auxiliary gain

QPUMP = + Pump gain.

- Losses:

QLOAD = - Energy to load:

TLOSS = – Tank loss

PLOSS = – Pipe loss

DE = - Internal energy change.

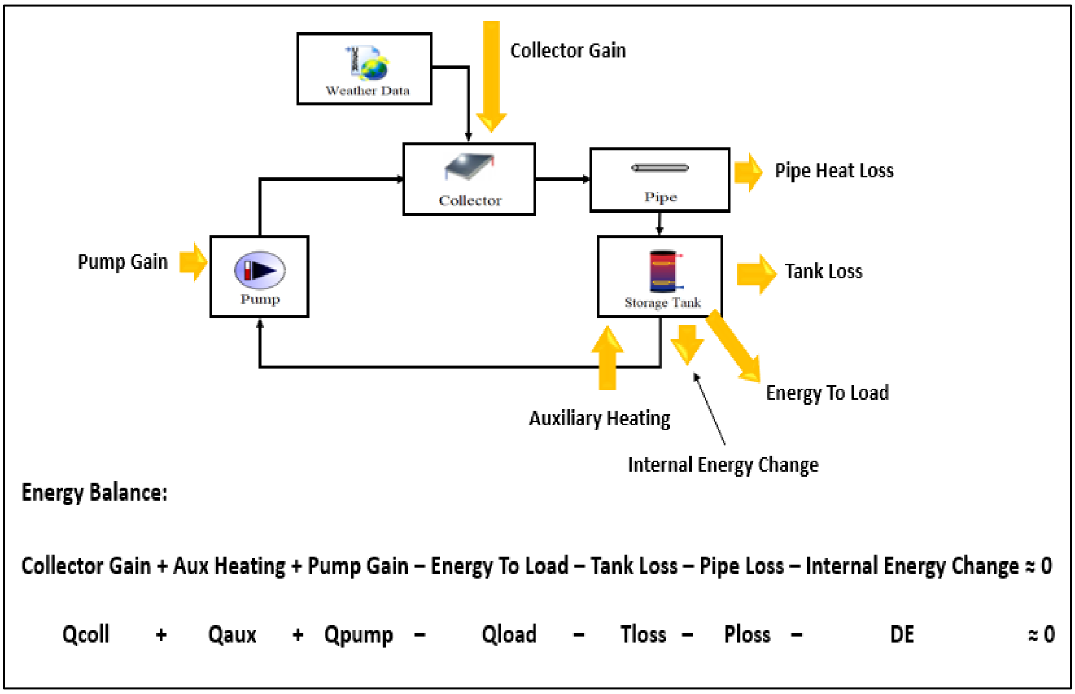

Figure 11: Illustration of the SDWH System Energy Balance Diagram.

Chapter 4

SIMULATION METHODOLOGY (TRNSYS & T*SOL)

4.1 Background

In this chapter, the details of the simulation methodology are explained. Two different simulation softwares TRNSYS and T*SOL, are used to simulate and evaluate the two different (FPC and ETC) solar water heating systems' performance in order to choose the most efficient and economical system.

4.2 Exploring TRNSYS Simulation Tool and Assembling the System

TRNSYS (Transient systems simulation program) is a simulation program for transient systems which uses a modular structure. The design and analysis of thermal or electrical energy systems are among the most used software. TRNSYS has a prosperous library of modules capable of modeling and simulating widely used thermal systems. By various arrangements of these components, modeling and simulating the simplest and most complex thermal systems is possible. Weather file components existing in TRNSYS enable to capture of the dynamic behavior of the weather. Thus, TRNSYS adapts very well to the system's actual behavior over time. (The Solar Energy Laboratory, 2017).

The flow chart (figure 12) illustrates the study plan of TRNSYS simulation for comparing the thermal performance of Solar Domestic Water Heaters SDWH using Evacuated Tube Collectors (ETC) and Flat Plat Collectors (FPC).

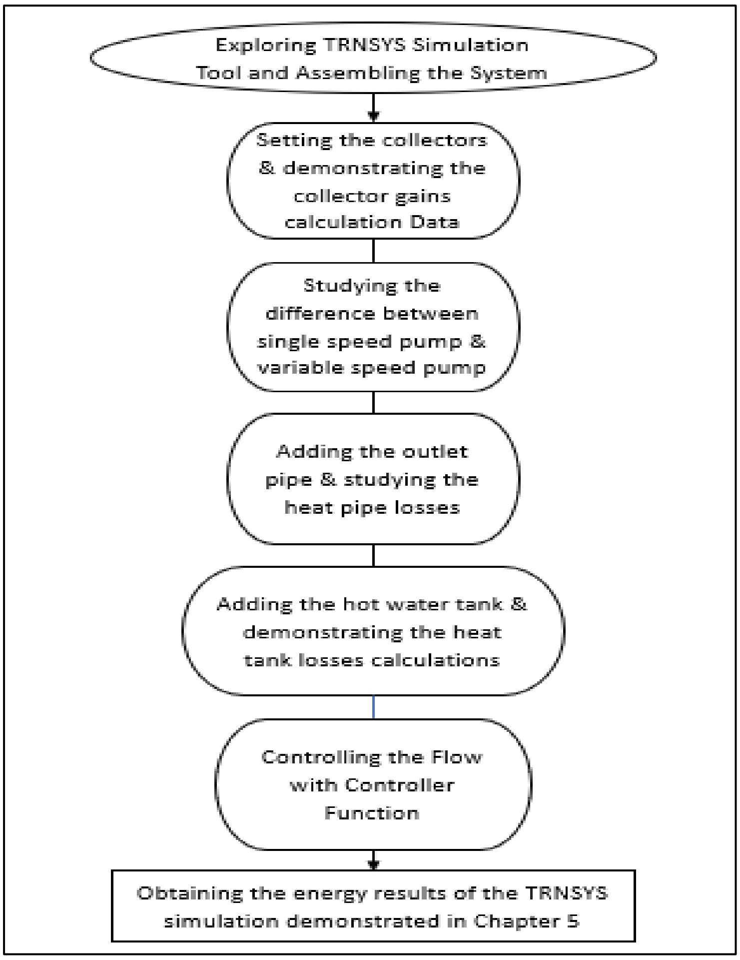

Figure 12: TRNSYS Simulation Study Plan

4.2.1 Setting the collectors and linking Weather Data

The modeling starts with setting up the collector component and connecting it to the plotter (the component that reads and reports the outputs) to read the outlet temperature and the collector's useful energy gains, calculated according to the mathematical model used TRNSYS.

Subsequently, the weather file component is linked to the solar collector of a (5 m^2) area (set on inclination angle = 30°). This step enables feeding the weather data such as radiation, ambient temperature, etc., stored in the weather file to the solar collector component. The weather file components involve (Meteonorm Weather File). For any location on Earth, Meteonorm generates precise and representative typical years. There are more than 8,000 weather stations, five geostationary satellites, and an aerosol climate database calibrated worldwide. For this study, the Beirut region is selected. The resulting layout is shown in figure 13.

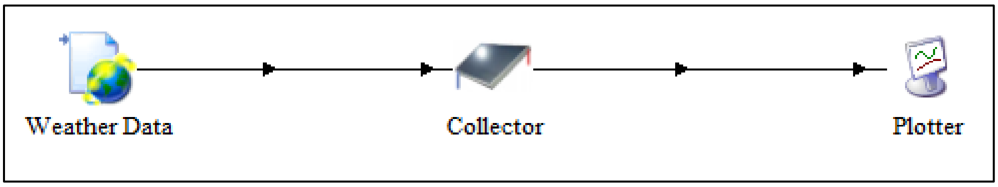

Figure 13: Layout of Links Between Weather Data, and Collector Components. (TRNSYS Software)

Simulating such a simple system helps observe the collector's temperature and the radiation rate on the collector's surface. These can be shown in figure 14 for January. Note that the chart's right-side ordinate in TRNSYS reports the radiation rate as (Heat Transfer Rate).

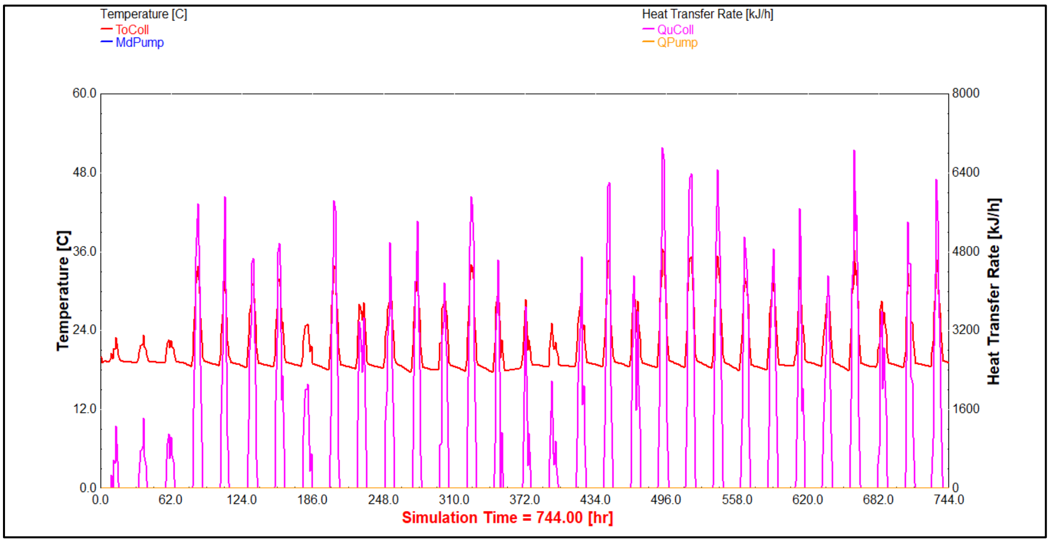

Figure 14: Temperature and the Heat Transfer Radiation over the Collector Surface (TRNSYS Software)

4.2.2 Adding Single Speed Pump

A pump should be added to the system to circulate the fluid through the collector. A single-speed pump or a variable speed pump can be installed. If a single-speed pump is added, the system layout is shown in figure 15. A single-speed pump gives a constant fluid mass flow rate through the system. Using a single-speed pump, start and stop behavior cannot be automatically controlled. The constant speed pump has the features, as shown in table 1:

Table 1: Single Speed Pump Features (TRNSYS Software)

Parameters	Value	Unit
Rated flow rate	200	[kg/h]
Fluid specific heat	4.19	[kJ/kg K]
Rated power	2684	[kJ/h]

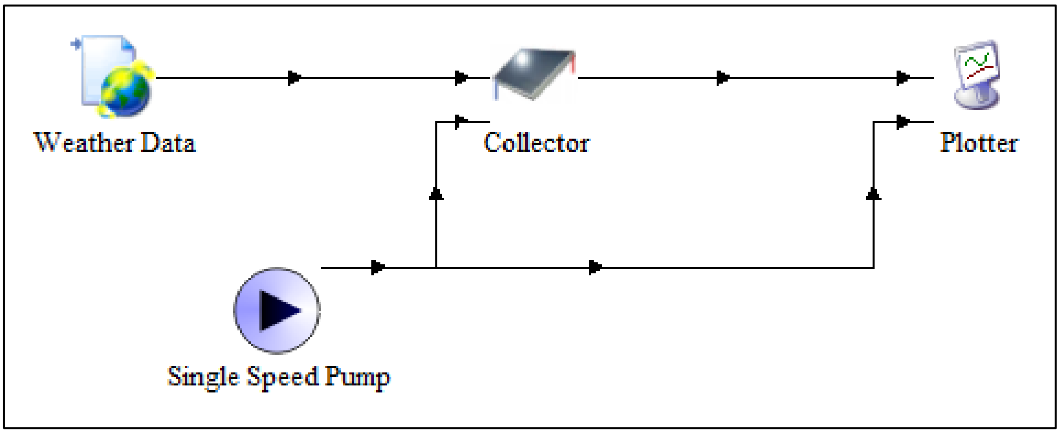

Figure 15: System Layout with Single-Speed Pump. (TRNSYS Software)

Simulating over the first week of January, as shown in figure 16, presents how the pump is continuously working with a constant flow rate of 200 [kg/hr]. Note that even in night times when there is no thermal energy collected by the collector (Qucoll is zero) the pump continues to run.

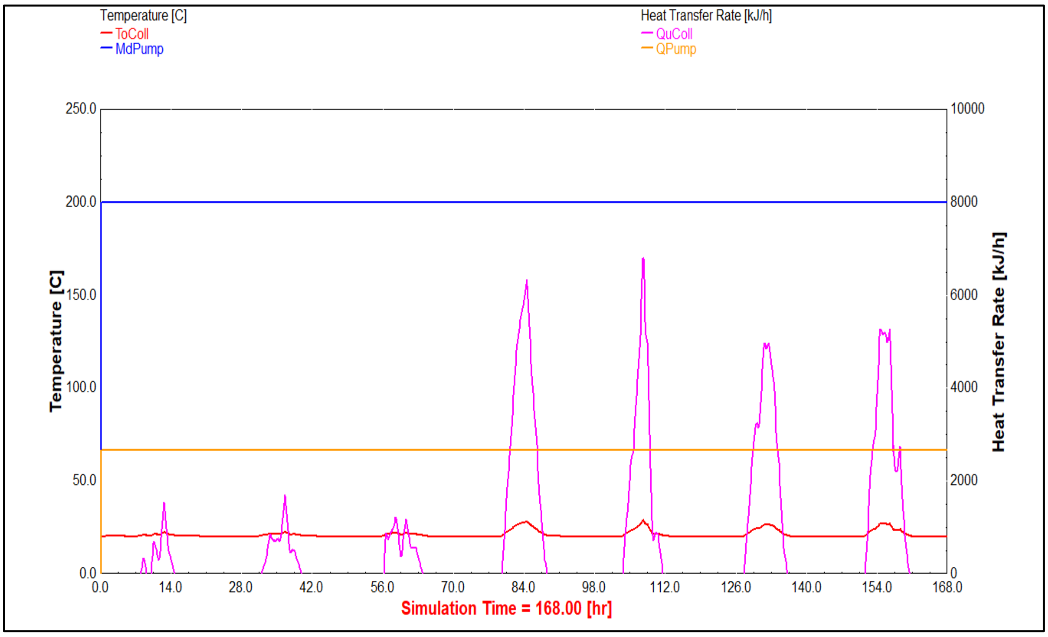

Figure 16: Simulating over the First Week of January (TRNSYS Software)

As shown in figure 16, the constant speed pump always operates and delivers 200 kg/hr of flow rate (MdPump) even if it is not necessary to work, making the system consume more energy. Nighttime running of the pump will result in losing thermal energy to the environment via the collectors; this contradicts the concept of having a renewable system that saves energy. Constant speed pumps stop only manually at night times and should be switched on again manually in the morning. The operation of continuous speed pumps should be controlled by a timer or differential thermostat. The differential thermostat allows the pump to operate only when the collector's fluid outlet temperature is higher than that in the storage tank.

4.2.3 Replacing the Single Speed Pump by a Variable Speed Pump

Replacing the single-speed pump with a variable-speed pump (figure 17) enables the system to operate at different mass flow rates varying between zero and the rated value. The downstream flow rate is based on flow rate input parameters set according to the control strategy. Thus, there is a requirement for a control unit. The Variable speed pump has the following features:

Table 2: Variable Speed Pump Features (TRNSYS Software)

Parameter	Value	Unit
Rated flow rate	200	[kg/h]
Fluid specific heat	4.19	[kJ/kg K]
Rated power	2684	[kJ/h]

The control unit sets the mass flow rate and energy transferred from the pump to the fluid stream to zero if it is considered turned off (based on the control strategy set).

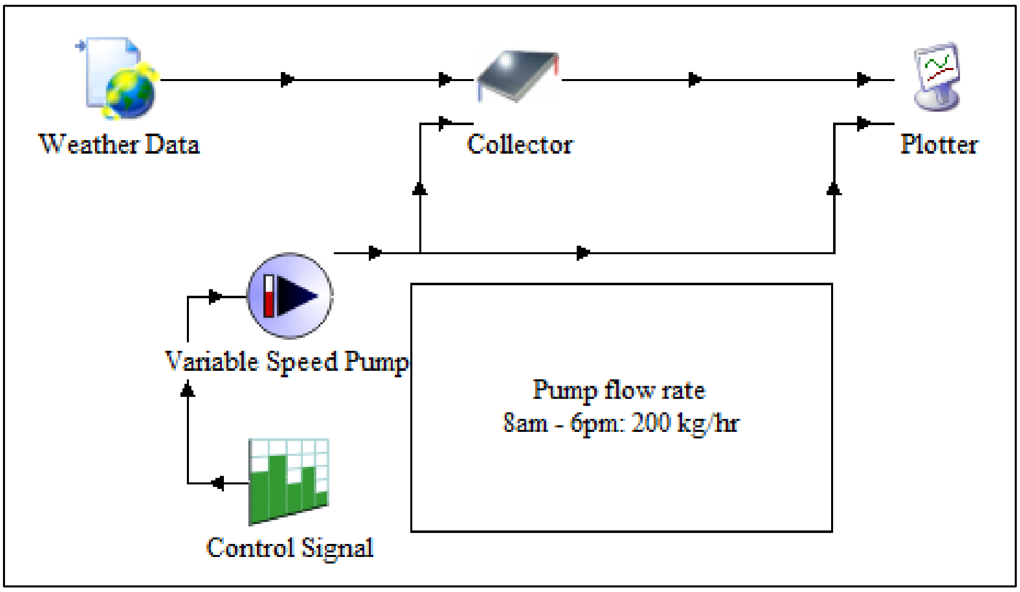

Figure 17: Replacing the Single Speed Pump with Variable Speed Pump (TRNSYS Software)

The control signal is linked to the variable speed pump and set on a pattern as on duty from 8 am to 6 pm (a period in which the Sun is available) (figure 18). Simulation results over the first week of January shown in figure 19 presents how the pump is switching on automatically and shutting down according to its set pattern time.

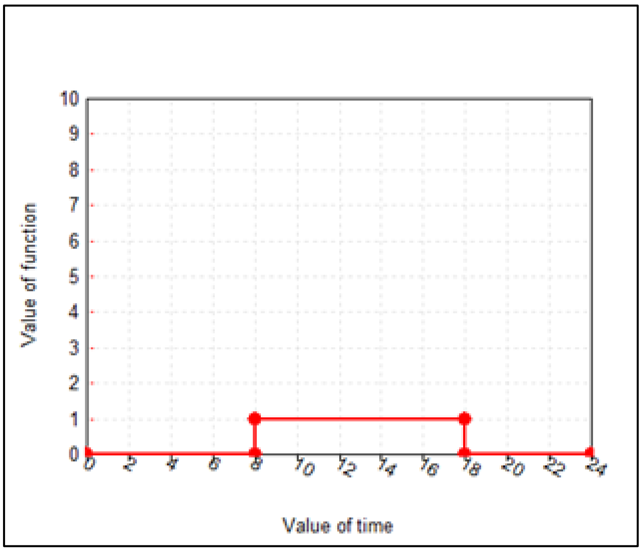

Figure 18: Control Signal to the Variable Speed Pump

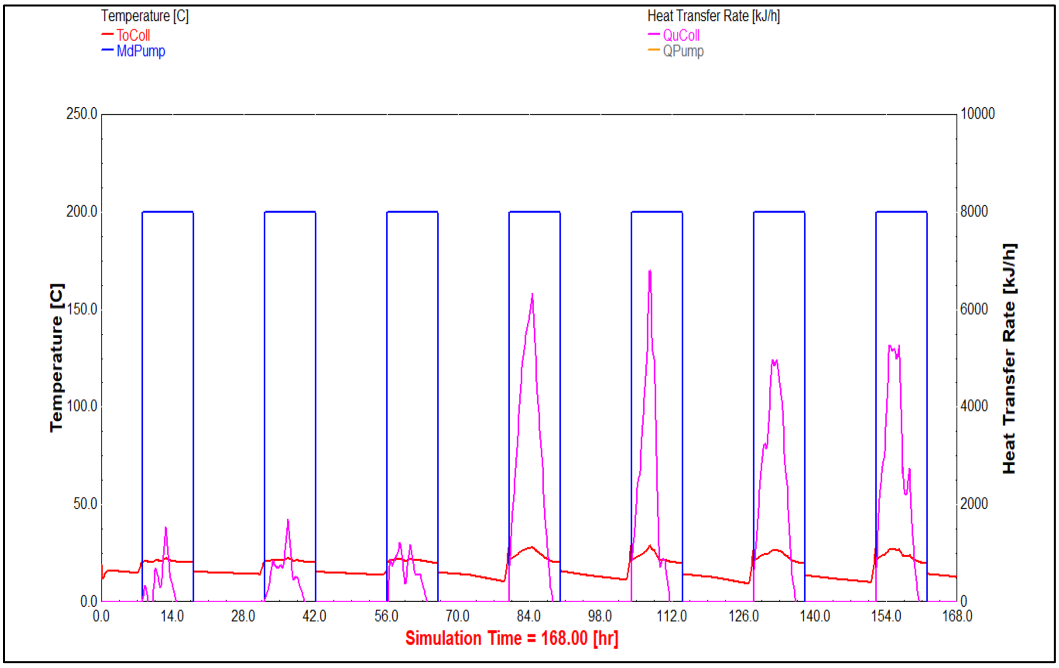

Figure 19: Simulating over the First Week of January (TRNSYS Software)

4.2.4 Variable Flow Rates Using Variable Speed Pump

To run the system more effectively and collect maximum energy, one can also control the flow rates during the operation times by controlling the pump speed. The pump flow rate can be reduced to [100kg/hr], between (8 am and 11 am) wherein the morning part of the day is not very hot. Then between (11 am and 2 pm); the hottest part of the day, one may increase the flow rate to [200kg/hr], and in the afternoon to a moderate speed to adjust the flow rate to150kg/hr as shown in figures 20, 21.

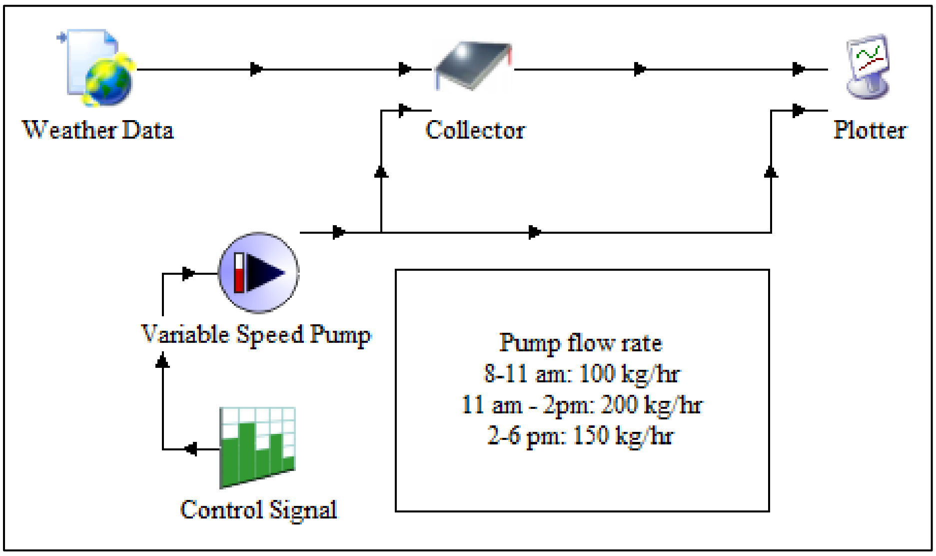

Figure 20: Setting Variable Flow Rates using Variable Speed Pump (TRNSYS Software)

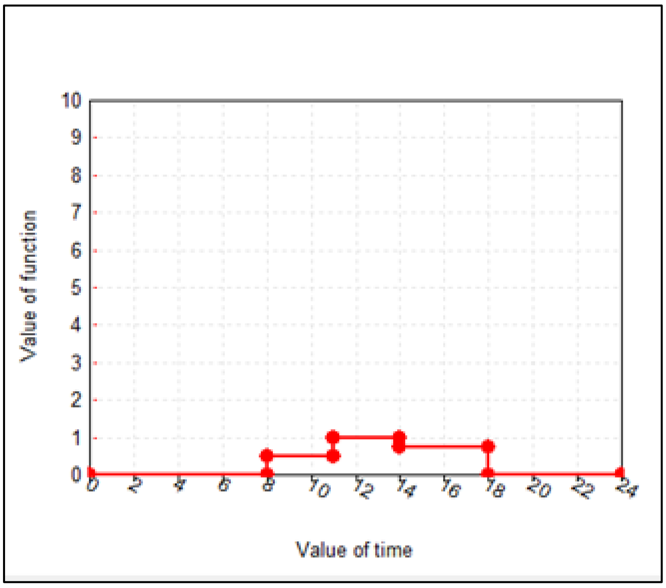

Figure 21: Control Signal Schedule to the Variable Speed Pump

After simulating over the first week of January, it is seen in figure 22 how the flow rate of the variable speed pump Mdpump is changing as planned during the day.

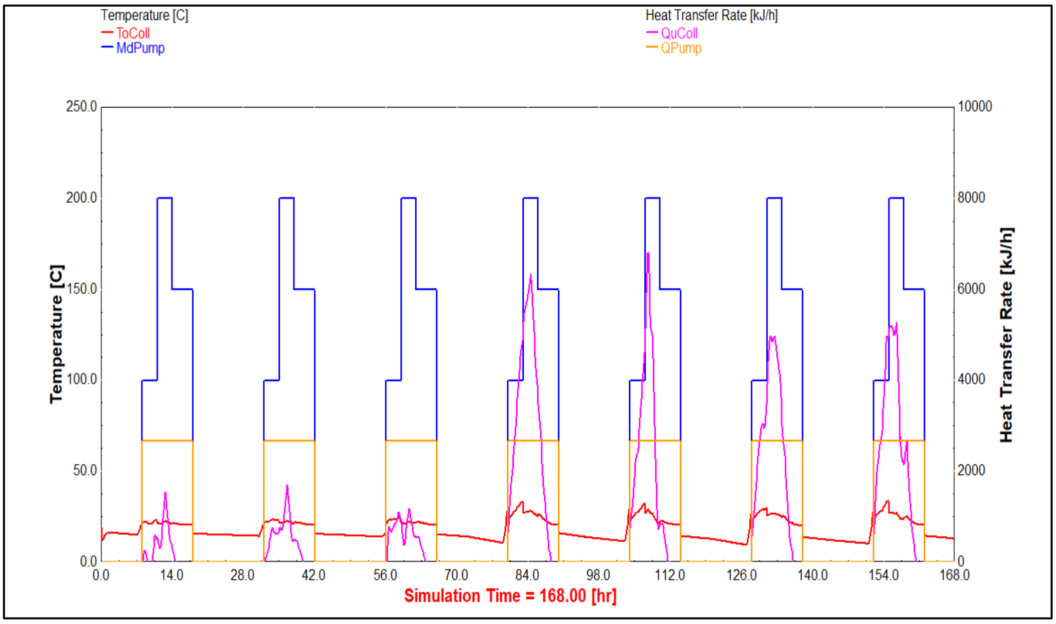

Figure 22: Simulating Variable Flow Rates over the First Week of January (TRNSYS Software)

4.2.5 Adding the outlet Pipe

Adding the outlet pipe to the model requires setting the pipe's parameters stated in table 3 and adding the pipe heat loss equation. The overall heat transfer coefficient (U) for the pipe is listed in equation 1.7.

Heat loss from pipes depends on fluid temperature, as well as the outdoor ambient temperature. Heat loss calculation is linked to the software equation and automatically calculated considering the temperature variations (figure 23).

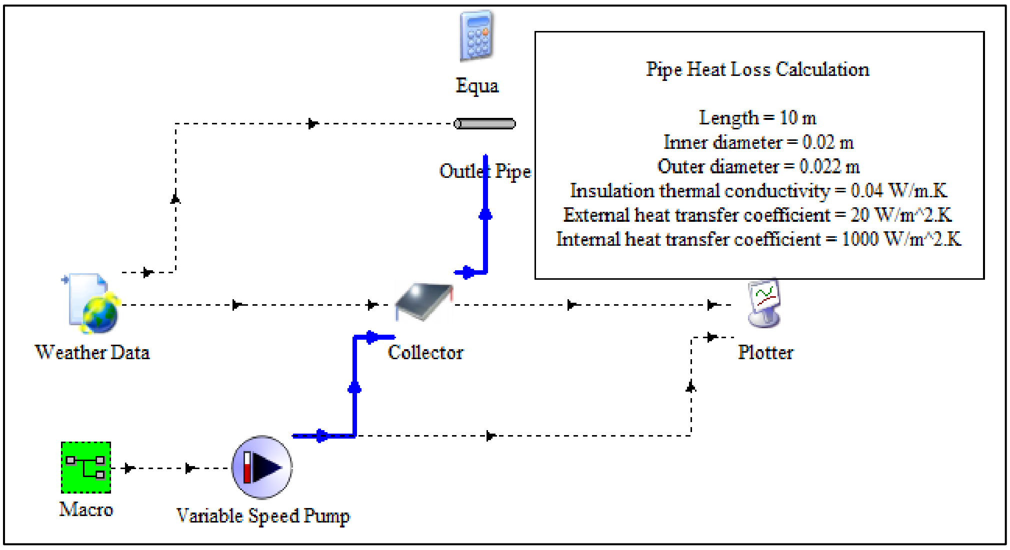

Figure 23: Adding the Outlet Pipe and Calculating the Pipe Heat Loss (TRNSYS Software)

Table 3: Pipe Parameters and Heat Loss (TRNSYS Software)

Name	Value	Unit
Inside Diameter (Di)	0.02	[Meter]
Outer Diameter (Do)	0.022	[Meter]
Pipe Length (L)	10	[Meter]
Fluid Density	1000	[kg/m^3]
Fluid Specific Heat	4.19	[kJ/kg K]
Internal Heat Transfer Coefficient (H_int)	1000	[W/m^2.K]
External Heat Transfer Coefficient (H_ext)	200	[W/m^2.K]
Insulation Conductivity of The Pipe (K_insul)	0.04	[W/m.K]
Inlet Temperature	T_i	[℃]
Outlet Temperature	T_{out}	[℃]
Environmental Temperature	T_{env}	[℃]
Pipe outer surface area	$A_{pipe} = \pi D_i L_{pipe}$	[m^2]

Loss Coefficient	$U = \dfrac{1}{\dfrac{1}{h_{int}} + \dfrac{D_i}{2k_{insul}} ln \dfrac{D_0}{D_i} + \dfrac{D_i}{D_0 h_{ext}}}$	[kj/hr.m^2.K]
Heat Loss to Environment	$\dot{Q}_{env} = UA_{pipe}(\dfrac{T_i + T_{out}}{2} - T_{env})$	[kj/hr]

4.2.6 Adding a Hot Water Tank

The hot water tank has different thermal levels, the coldest water is at the bottom, and the hottest water is at the top. This leads to more efficient solar hot water performance because the coldest possible water is sent to the collector to have the greatest possible thermal gains and lower the collector's temperature rise. Furthermore, the stored hottest water at the top of the tank is delivered to the load, assisting in maintaining the hot water supply temperature variation. The selected tank storage parameters are listed in the following table 4:

Table 4: Storage Tank Parameters (TRNSYS Software)

Name	Value	Unit
Heat Tank Volume	450	[Liter]
Fluid Specific Heat	4.182	[kj/kg.K]
Water density	1000	[kg/m^3]
Heat Tank loss Coefficient	2.5	[kj/hr. m^2.K]
Maximum heating rate of element	9000	[Kj/hr]
Boiling Point Inside the tank	100	[℃]

4.2.7 Setting Up Tempering Valve and Flow Mixer

Mixing heated fluid with colder supply fluid is typical in domestic, commercial, and industrial heating applications so that the flow stream to the load is not warmer than required. This is also done by inserting a tempering valve (mixing valve) in the stream of the storage inlet and the cold-water line supply to a load, as shown installed in position B (figure 24). The pre-adjusted mixing valve set on position A ensures that people are not harmed by hot water delivered to the load.

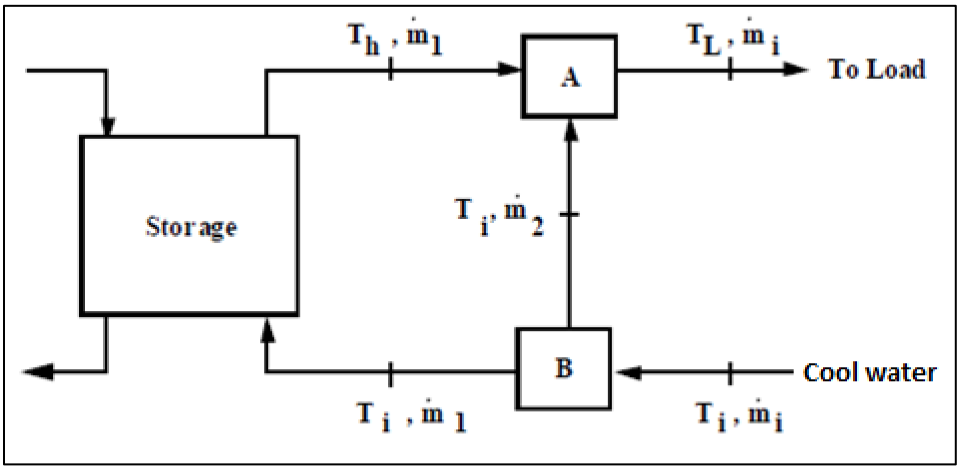

Figure 24: Tempering Valve and Mixing Valve (The Solar Energy Laboratory, 2017)

The mixing valve outlet temperature is given in the following equation:

$$T_L = \frac{m_1 T_h + m_2 T_i}{m_1 + m_2} \tag{4.1}$$

4.2.8 Controlling the Flow with Controller Function

The control function has a signal γ_0 that controls the pump's ON, OFF switching. ΔTH (the upper dead-band temperature difference) is the temperature difference of the fluid carried by the feed pipe going from the collectors' outlet to the tank loop heat exchanger. However, ΔTL (the lower dead band temperature difference) is the temperature difference of the fluid carried in the return pipe from the tank back to the collector.

- ΔTH: upper dead band temperature difference
- ΔTL: lower dead band temperature difference
- TH: average upper dead band temperature
- TL: average lower dead band temperature.

Mathematically, the control function is expressed by:

- If the controller was previously ON ($\gamma_0 = 1$):
- If $\Delta TL \leq$ (TH - TL) then $\gamma_i = 1$
- If $\Delta TL >$ (TH - TL) then $\gamma_i = 0$.

If the controller was previously OFF ($\gamma_0 = 0$):

- If $\Delta TH \leq$ (TH - TL) then $\gamma_i = 1$
- If $\Delta TH >$ (TH - TL) then $\gamma_i = 0$.

However, the control function is set to zero, irrespective of the upper and lower dead bands if the tank's temperature is above a certain specified maximum, that is 90 ^{o} C.

The role of the controller is represented graphically in figure 25.

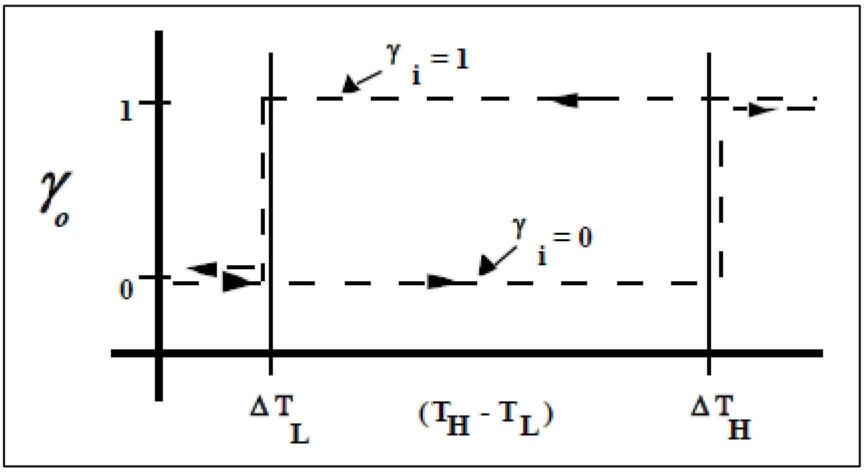

Figure 25: Controller Function (The Solar Energy Laboratory, 2017)

4.2.9 Calculating Daily and Monthly efficiencies of both FPC, ETC

The following equations calculate the daily and monthly efficiencies of both ETC and FPC systems:

$$\text{Daily Efficiency} = \frac{\text{Collector Heat Gain}}{\text{Incident Radiation}} \tag{4.2}$$

$$\text{Incident Radiation} = IT_{Daily} * A_{coll}$$

$$\text{Monthly Efficiency} = \frac{\text{Collector Heat Gain}}{\text{Incident Radiation}} \tag{4.3}$$

$$\text{Incident Radiation} = IT_{Monthly} * A_{coll}$$

- IT_{Daily} Radiation collector tilted surface
- A_{coll} is the Collector Area = 5 m^2.

Both equations 4.2 ,4.3 are loaded in the (equation code) inside the simulation linked to the integrator (figures 26, 27). The integrator role is to integrate both the collector's useful gain and the incident radiation over the selected period, either over days or months.

4.2.10 Setting Simulation Summary of Both FPC, ETC SDWH Systems

The output Simulation Summary Code is linked with all the units: the collector, outlet pipe, solar storage tank, auxiliary heating, and pump. The simulation code will output all the Pipe heat loss data, tank loss, internal energy change, energy to load, pump gain, collector gain, and auxiliary heating and are divided into two categories Losses and Gains.

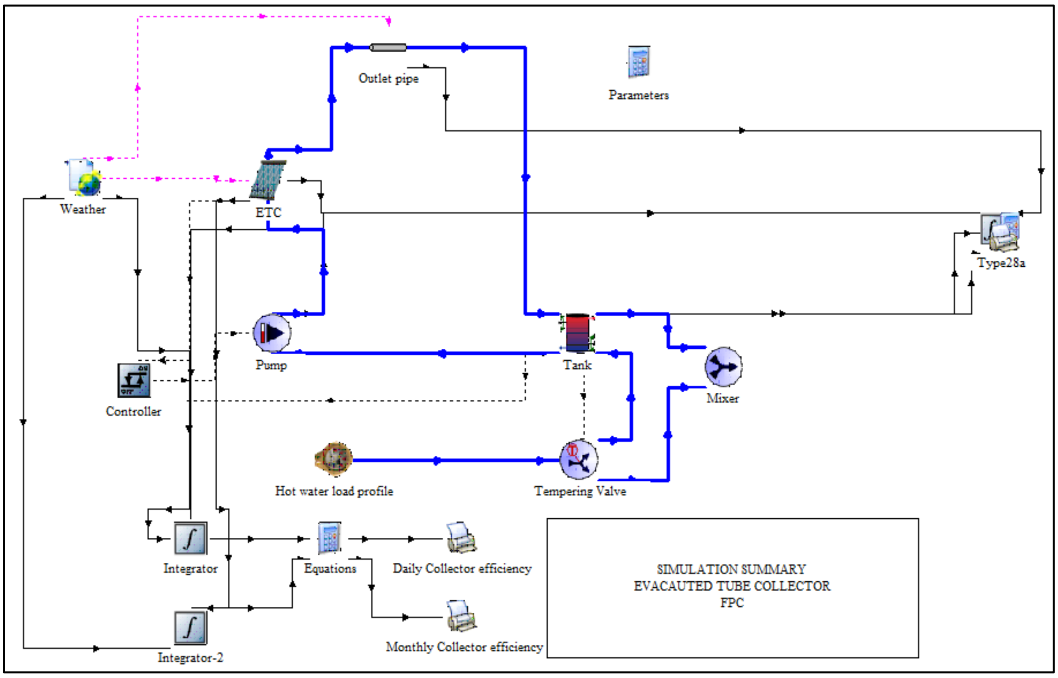

Figure 26: System Topology of SDWH using ETC Simulated with TRNSYS (TRNSYS Software)

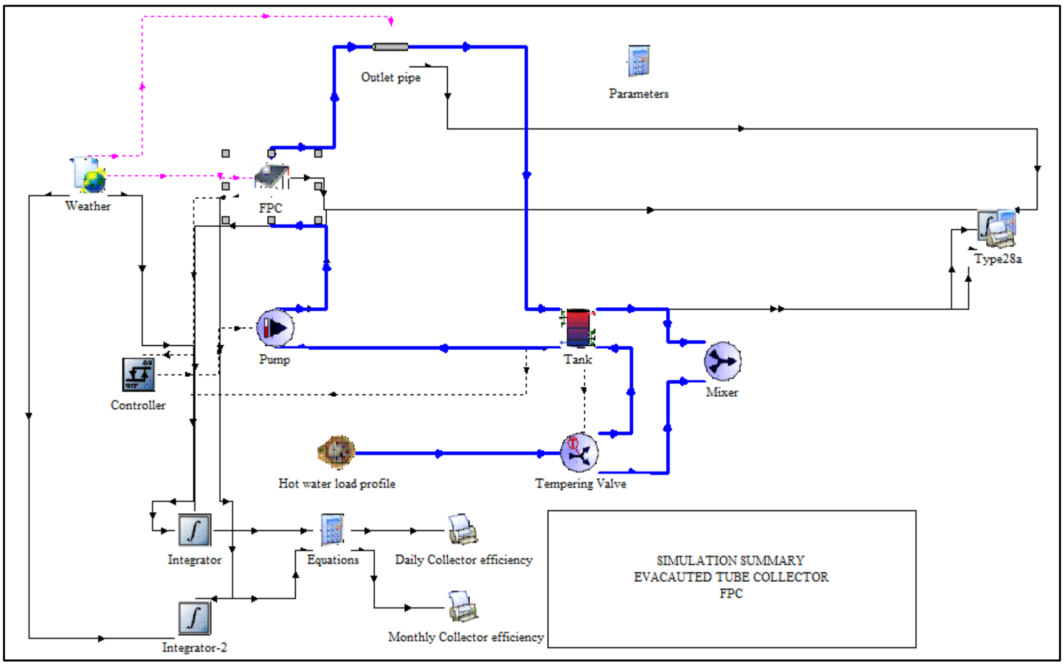

Figure 27: System Topology of SDWH using FPC Simulated with TRNSYS (TRNSYS Software)

The result of the TRNSYS simulations shown in figure 26,27 will be elaborated in chapter 5 (Energy Simulation Results).

4.3 Exploring T*SOL Simulation

The second simulation tool will be applied to solar collectors by building two SDWH Systems using Valentin T*SOL simulation software. T*SOL is software for designing and simulating water heating systems in small and largescale applications. T*SOL software is designed to simulate solar systems. It offers a database of several accredited solar collectors evaluated and certified by independent organizations in compliance with the Solar Collector Certification Program (SRCC). (Valentin, 2013).

The flow chart (figure 28) illustrates the study plan of T*SOL simulation for comparing the thermal performance of Solar Domestic Water Heaters SDWH using Evacuated Tube Collectors ETC and Flat Plat Collectors.

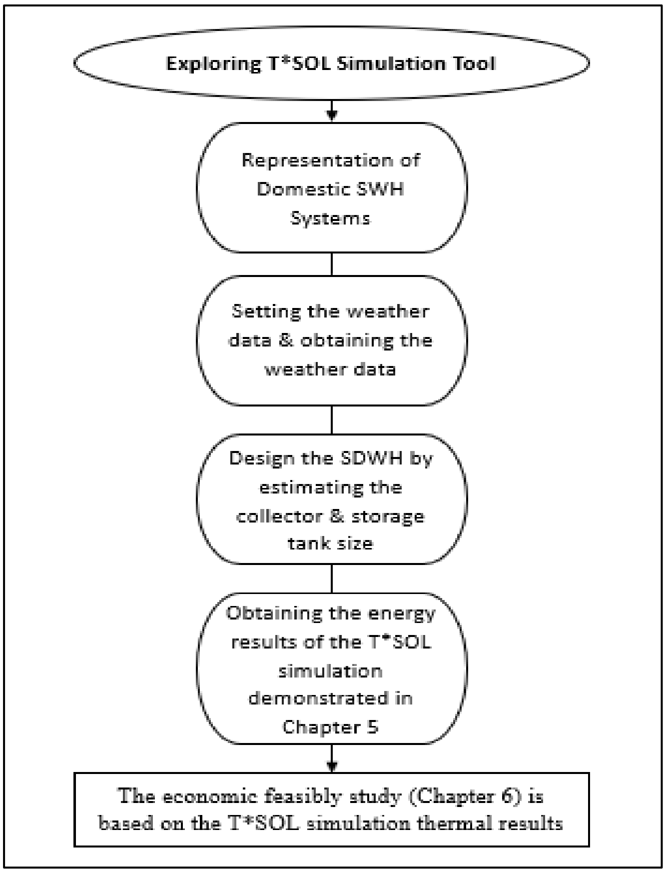

Figure 28: T*SOL Simulation Study Plan

4.3.1 Representation of Domestic SWH Systems

A solar thermal system collector in SDWH comes mainly in two types FPC, ETC whose performance is studied and compared in this simulation study. Also, according to their operation, solar heaters are classified into two types, Natural circulation and Forced circulation.

Natural circulation: in this type, the fluid of the system is water itself, and when heated in the solar heater, it rises due to convection and flows to the hot water storage tank, which must be located higher than the panel. The heated water stored in the storage tank is supplied to the consumption points. As the water is consumed is replaced by the external inflow.

Forced circulation: This is a closed piping circuit between the panel and hot water storage tank and contains a heat exchanger coil within the storage tank and a pump. The pump, also called (circulator) enables the heat collected by the fluid to be transferred to the heat exchanger coil inside the storage tank. The circuit is considerably more complicated; it has a temperature control unit and other parts and requires electricity for the pump and the control unit. The storage tank may not need to be leveled above the panels. The storage tank may be mounted indoors and therefore is less susceptible to nighttime heat losses or adverse weather conditions. These systems, in general, have a much higher thermal efficiency. The system simulated by T*SOL simulation is a forced circulation system.

4.3.2 Demonstrating the SDWH System

The major component of the SDWH device is the collector that transforms solar energy into heat and transfers it to the storage tank by heat transfer through pipes and heat exchanger systems. In water heating systems, the hot water storage tank helps compensate for the variations in energy supply and demand at various times throughout the day. In the case of inadequate solar energy, the auxiliary heating system provides the balance of energy to cover the requirements. A controller controls the solar system's operating state, controlling the pump ON, OFF settings according to the temperature range difference between the hot storage tank and the collector.

4.3.3 Setting Weather Data

The ambient temperature, solar radiation, and wind velocity data of Beirut, Lebanon (Latitude: 33.9, Longitude: -35.5) is chosen from the MeteoSyn Tool Database. The simulation analysis was carried out at hourly steps for a year period, using the data extracted from MeteoSyn, Database. Typical annual weather indicators for Beirut city are as follows:

- Mean outside temperature: 20.9 ℃
- Lowest outside temperature: 6.5 ℃
- Total annual global irradiation: 1837.1 kW/m^2
- Diffuse radiation: 41%.

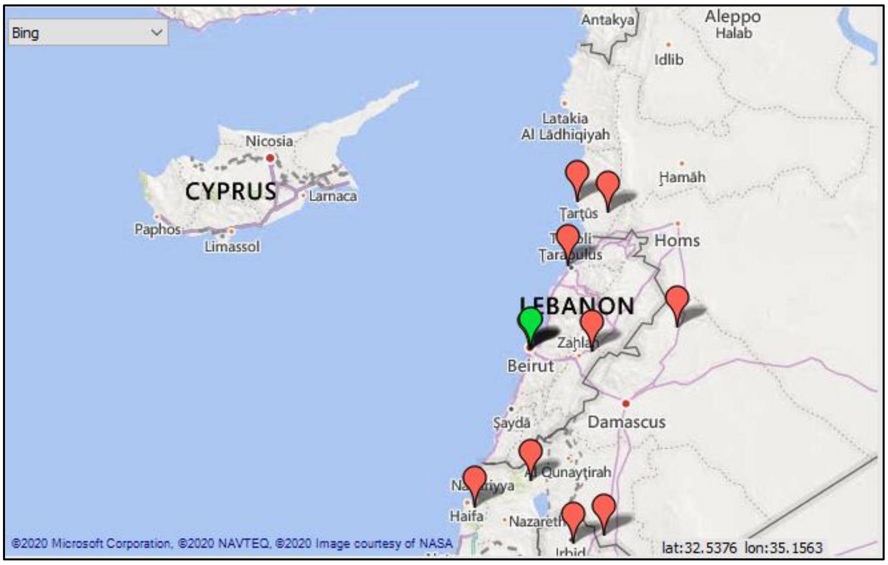

Figure 29: Beirut, Lebanon Location (MeteoSyn, Database)

Lebanon has a Mediterranean climate. The winter is warm, short, and rainy, and the summer is long and hot and dry.

The following is a graphical show of Beirut city weather data (figure 30,31):

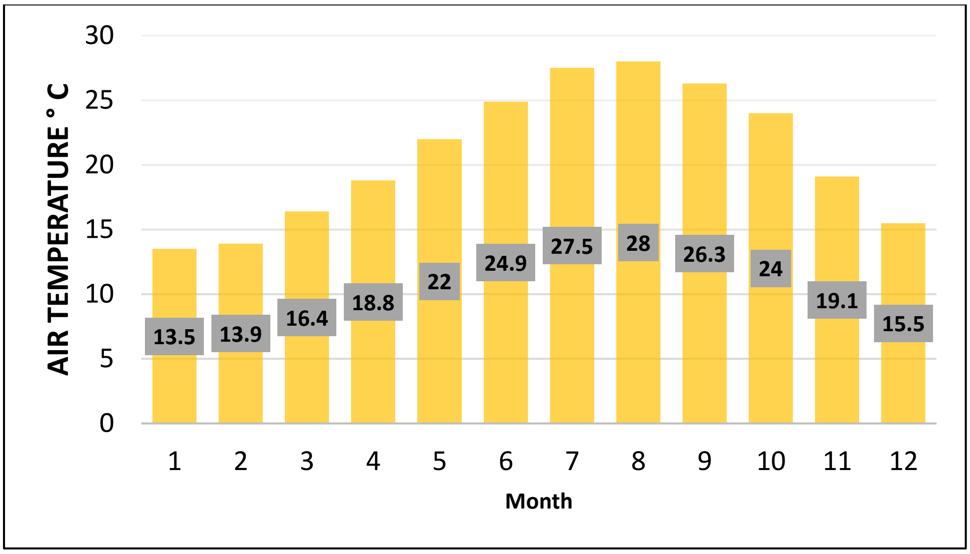

Figure 30: Monthly Mean Annual Air Temperature Distribution in Beirut (MeteoSyn, Database)

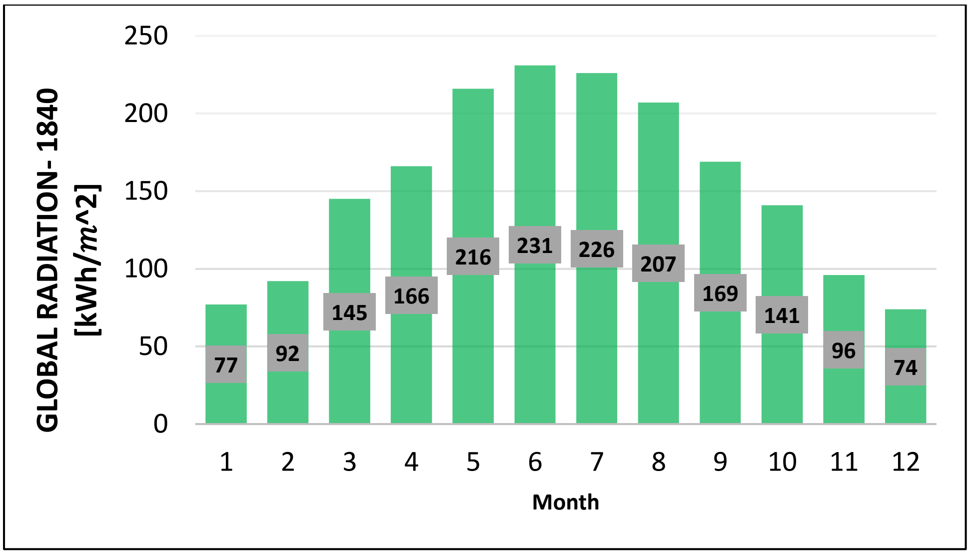

Figure 31:Monthly Mean Global Radiation in Beirut (MeteoSyn, Database)

4.3.4 Arranging Thermal Collectors ETC and FPC

Domestic solar water heaters for private houses are designed to supply the whole demand for hot water supply outside each day's heating period. In this way, a large part of the annual hot water supply requirement can be obtained from solar energy. An efficiently designed system should provide at least half of the heating energy to heat the water during the fall and winter seasons.

Two similar identical systems are built using different collectors:

- Flat plate Collector
- Evacuated tube collectors.

Flat plate collector: include a metal absorber in an insulated box with a transparent cover on top and heat insulation on the rear. The transparent cover reduces the irradiation that wants to escape from the collector absorber back to the environment. The heat insulation decreases the heat lost from the collector's back side, allowing temperatures above 150 ° C to be achieved within the collector box. The heat collected and transferred from the collector is used for water heating, space heating, and heat generation. (Valentin, 2013)

Evacuated tube collector: has a sealed absorber in evacuated tube pipes. The vacuumed tubes reduce the heat loss, allowing temperatures to be reached above 200 ° C to be used for water heating, space heating, and process heat generation. (Valentin, 2013)

Before choosing the collectors, the collector sizes shall be estimated, and then suitable collectors shall be picked up from the library of T*SOL. The collector size can be calculated using the following equation:

$$A_C = \frac{L}{\eta_S * I_r} = \frac{10}{0.4*5} = 5m^2 \tag{4.4}$$

- Ac = collector area needed to meet the daily demand of hot water consumption $[m^2]$
- L = Daily load to produce hot water; 10 kWh calculated by equation 4.2.
- η_S = efficiency of solar system assumed, 0.4
- I_r = Mean daily solar radiation in Lebanon is 5 $\frac{\mathrm{kWh}}{m^2}$/day.

The following equation estimates the daily load for hot water production:

$$\mathrm{Q_L} = m_L\, \mathrm{C_p}(\mathrm{T_O} - \mathrm{T_L}) \tag{4.5}$$

- $\mathrm{Q_L}$: Load heat energy KJ
- m_L : Mass of water consumption
- $\mathrm{C_p}$: Specific heat of water (4.19 kJ/kg K)
- $\mathrm{T_O}$: Mean Outside temperature in winter season 16 ° C
- $\mathrm{T_L}$: Desired load temperature 45 ° C.

$$\mathrm{Q_L} = \mathrm{m_L}\, \mathrm{C_p}(\mathrm{T_O} - \mathrm{T_L}) = 300 * 4.19 * (45 - 16) = 36453\ \mathrm{KJ} = 10\ \mathrm{kWh}$$

This data will be taken as a basis to search for an appropriate size of collector.

T*SOL provides an up-to-date database of many approved solar collectors tested and certified by independent organizations under the Solar Collector Certification Program (SRCC). (Valentin, 2013)

A parallel comparison was made with some of the best brands of solar collectors in the market; the simulation represented the flat plate collector and evacuated tube collector; the types KSC-AE/200/S and OPC 15 are chosen from those collectors. The SDWH device is formed of three collectors connected in series, as shown in figures 32, 33. Here, the second and subsequent collectors' outlet temperature would be more than the first since its outlet temperature is the next collector's inlet temperature. The water absorbs more and more energy along the way. The SDWH system parameters are listed in (table 5).

4.3.5 Storage Tank Size

In all solar heating water systems, the hot water storage tank's role is to store hot water while the collector absorbs the solar energy when Sun is shining and use it whenever required. The tank has a spiral heat exchanger where the solar collector's fluid circulates to transfer heat energy to the storage tank's water.

The hot water storage tank volume capacity should be enough to cover the whole day's demand. The average consumption in Liters is 75 Liter per person a day. If we assume the average family size is five-persons, the residency should require a 375 Liter, but if we consider accommodating gussets requirements, the tank is increased by 20%. In this case, a 450 Liter hot water storage tank is installed. Every storage tank should be insulated to retain the heat inside and decrease the losses to the medium surrounding the tank.

Table 5: SDWH System Parameters

Solar Collector		
Parameter	**ETC**	**FPC**
Collector Type	"OPC 15"	"KSC-AE/ 200/ S"
Active area of collector	1.72 m2	1.7 m2
Collector Numbers	3	3
Active area of collector	5.16 m2	5.1 m2
Inclination of collector	30°	30°
Temperature of inlet water	16 °C	16 °C
Storage Tank		
Type	Dual coil indirect	
Volume	450 Liter	
Height	1.8 m	
Tank insulation material	Mineral Wool	
Tank insulation thickness	100 mm	
Pump		
Volume flow rate	200 L/hr	
Auxiliary Heater		
Type	Electric	
Efficiency	78 %	

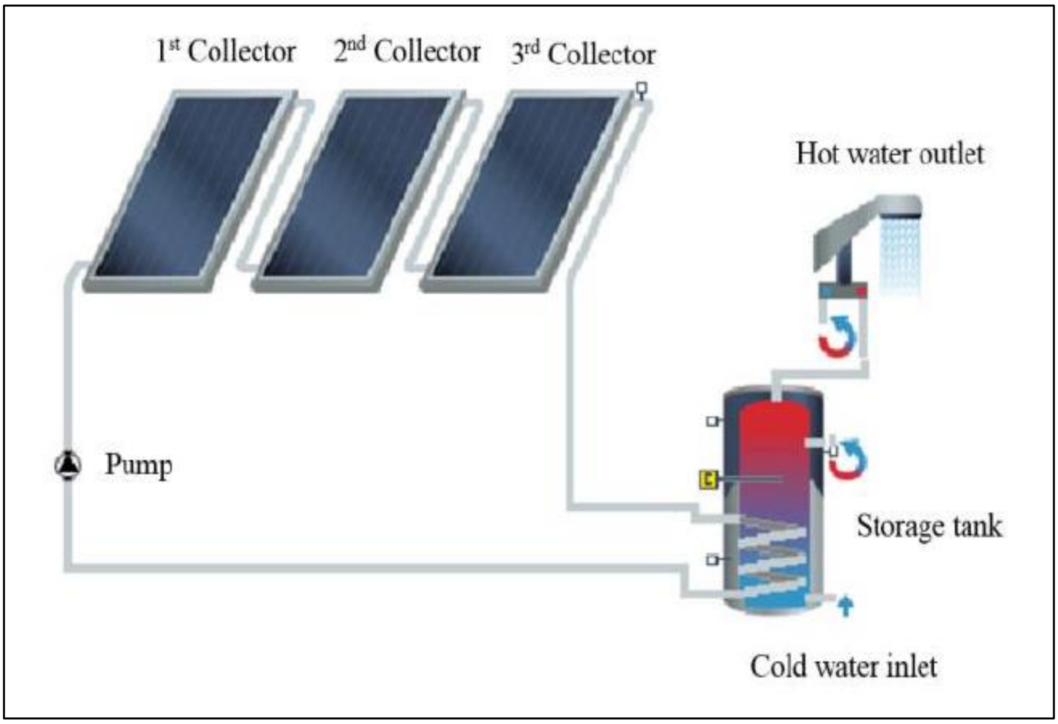

Figure 32: Schematic diagram of FPC SWH System (T*SOL software)

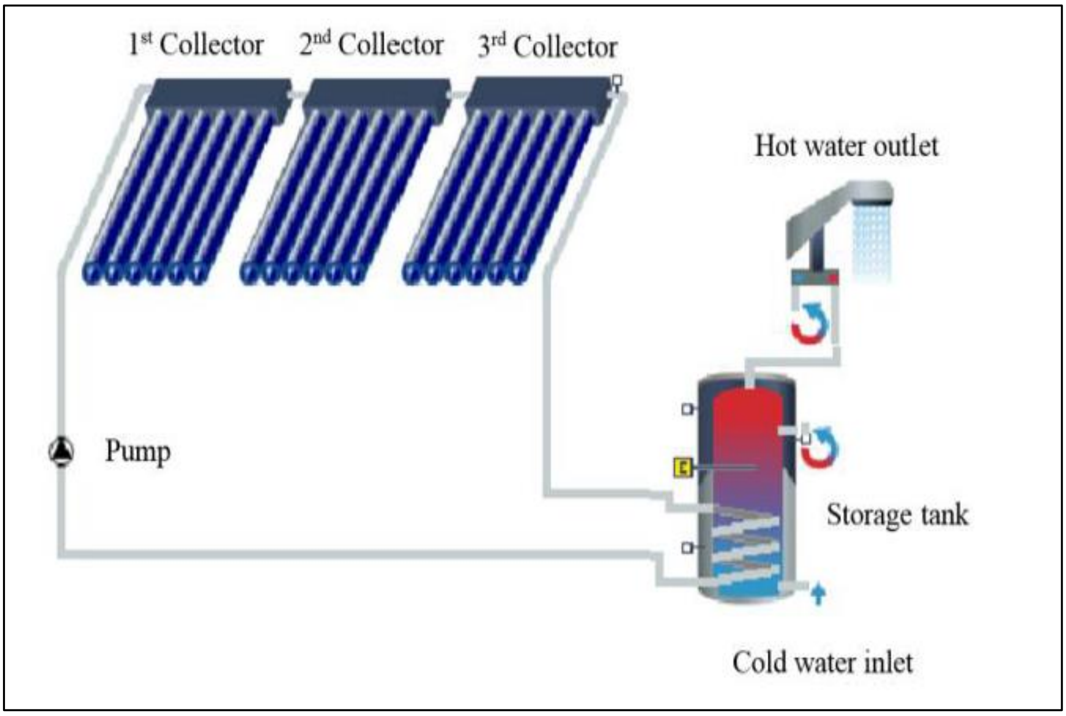

Figure 33: Schematic Diagram of ETC SWH System (T*SOL software)

Arranging the three collectors' positions is according to figure 34 using table 6 position parameters. The solar collector tilt angle (Beta) is chosen according to several angles while simulating the system where the collectors set on 30º tilt angles had the best energy gains collected.

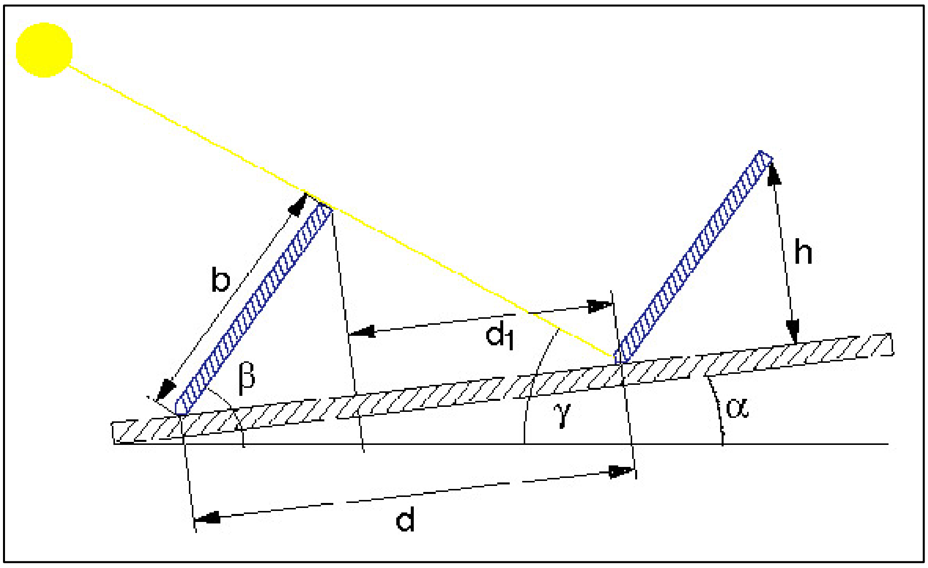

Figure 34: Arranging the Position of Collectors (T*SOL software)

Table 6: Arranged Collectors Position Parameters

Description	Value
b	1.25 m
h	0.62 m
Beta	30 ◦
Gamma	32.66 ◦
d	2.06 m
d1	0.97 m

The efficiency of the collectors placed in series is the ratio of useful energy gains during a specific period over the incident energy at the same time, and it will be calculated in the equations as follows:

$$\eta_{collector} = \frac{Q_u}{A_p I} \tag{4.6}$$

- $\eta_{\,1st\ collector} = \frac{\dot{m}\ C_p(T_2 - T_{fi})}{I\ A_{C1}}$
- $\eta_{\,2nd\ collector} = \frac{\dot{m}\ C_p(T_3 - T_2)}{I\ A_{C2}}$
- $\eta_{\,3rd\ collector} = \frac{\dot{m}\ C_p(T_{f0} - T_3)}{I\ A_{C3}}$
- $\eta_{\,overall\ collectors} = \frac{\dot{m}\ C_p(T_{f0} - T_{fi})}{I\ A_C}$

4.3.6 Pump Specification

A pump is used in solar collectors to circulate water between the hot water storage tank and the collectors. The temperature difference between the collector temperature and the water stored in the tank controls the pump's working in ON and OFF mode.

4.3.7 How Controller Works

Solar systems use a differential temperature controller. This controller compares the temperatures in the absorber and in the storage tank. The circulation pump turns ON as the absorber temperature becomes a pre-adjusted level above the storage tank's water temperature level. In the absorber device, the irradiation energy converted to heat is transferred to the storage tank; this makes the water temperature in storage increase. When the hot storage tank water temperature becomes equal to the absorber temperature, the pump turns OFF since there is not enough energy to supply any additional heat to the hot water tank. (Valentin, 2013)

4.3.8 Calculating Efficiencies and Solar Fraction

The collector Efficiency is defined as follows: (4.7)

$$\text{Collector Efficiency} = \frac{Energy\ output\ from\ the\ collector\ loop\ via\ the\ heat\ exchanger}{Energy\ irradiated\ onto\ the\ collector\ area\ (active\ solar\ surface)}$$

The system efficiency is defined as follows: (4.8)

$$\text{System Efficiency} = \frac{Energy\ output\ from\ the\ solar\ system}{Energy\ irradiation\ onto\ the\ collector\ area\ (active\ solar\ surface)}.$$

The solar fraction is defined as follows: (4.9)

$$\text{Solar fraction} = \frac{Energy\ supplied\ to\ the\ storage\ tank\ from\ the\ solar\ system}{The\ energy\ supplied\ to\ the\ storage\ tank(solar\ system+auxilary\ heating)}$$

The result of the simulations T*SOL simulation will be elaborated in chapter 5 (Energy Simulation Results).

Chapter 5

ENERGY SIMULATION RESULTS

5.1 Result of TRNSYS Simulation

The TRNSYS simulation studied focused on comparing two types of Domestic Solar Water Heater SDWH. The first type uses Flat Plate Collector FPC, and the second is using Evacuated Tube Collector ETC. The collector's comparison of performance analysis is performed using the parameters and energy equations listed in the previous Chapter (Simulation Methodology TRNSYS & T*SOL). The result shows how the energy collected by the collectors is varying over twelve months. The effect of weather fluctuation throughout the year on the performance of both types of solar heaters will be analyzed and explained.

5.1.1 Energy Gains and Solar Collector Temperature

The results show the difference in gained energy between the collectors, ETC giving better values. The energy gained by the ETC is more than energy collected by FPC by 15.23% in January, which is the lowest monthly gain, and the annual mean difference in gain is 12.55%. Both collectors, ETC and FPC, recorded their highest energy gains in August by 576 kWh; 519 kWh, respectively, as shown figure 35 during the summer season.

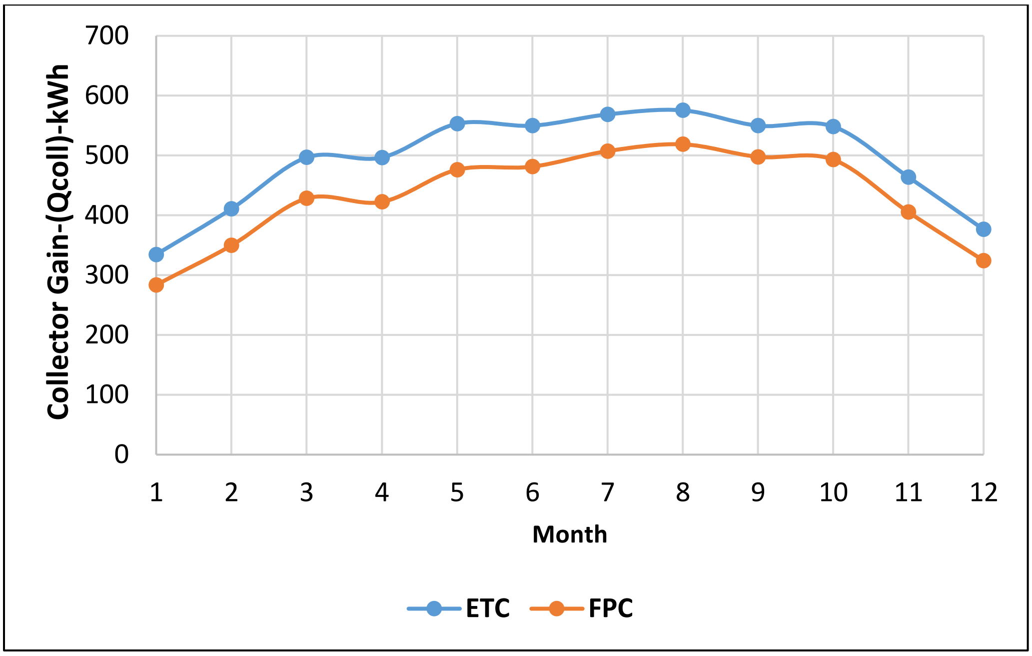

Figure 35: Collector Gain (Qcoll) kWh (ETC, FPC)

The identical amount of irradiation falling on the active solar area is shown figure 36 for both ETC and FPC, which gives a fair compression when calculating the collector efficiency.

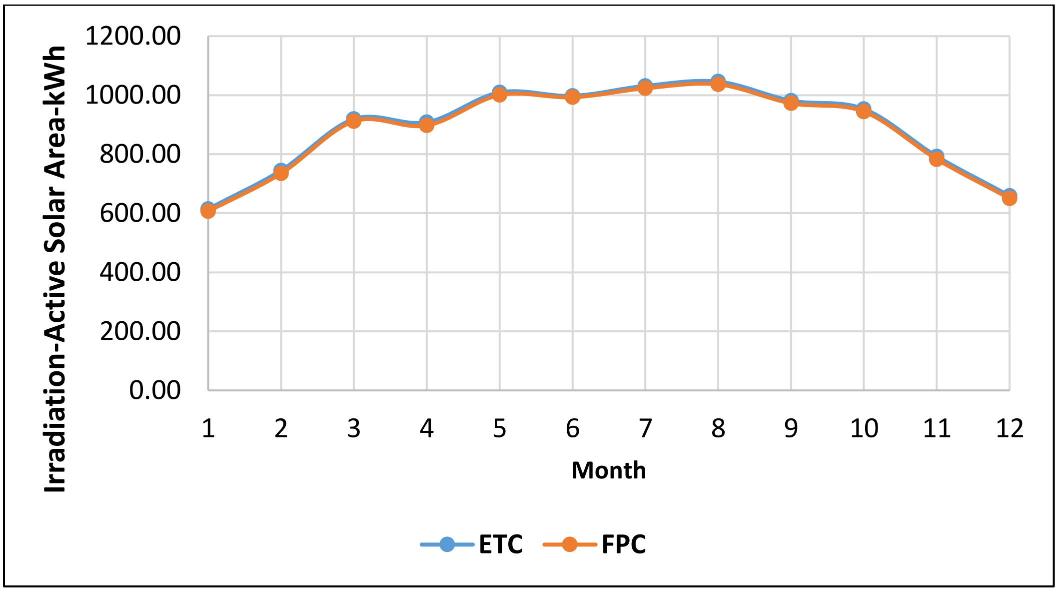

Figure 36: Irradiation on Active Solar Area

5.1.2 Auxiliary Gains

The auxiliary tank should only work when the solar gains are not sufficient to support heating to reach the desired water temperature.

During the six months from May to October, there is minimal need for auxiliary heating to support the hot water production. The superiority of ETC over FPC is observed in figure 37. The system needs more auxiliary heating support in March and September. However, auxiliary heating requirement peaks during winter months; December, January, and February, when the weather is cold and daily sunny periods are lowest. There is a bigger advantage in saving energy by the ETC over the FPC. The need to use auxiliary heating is lower by 524 kWh annually (figure 37), which is a significant amount of energy. This will add to savings, make the system more efficient and help mitigating carbon emission.

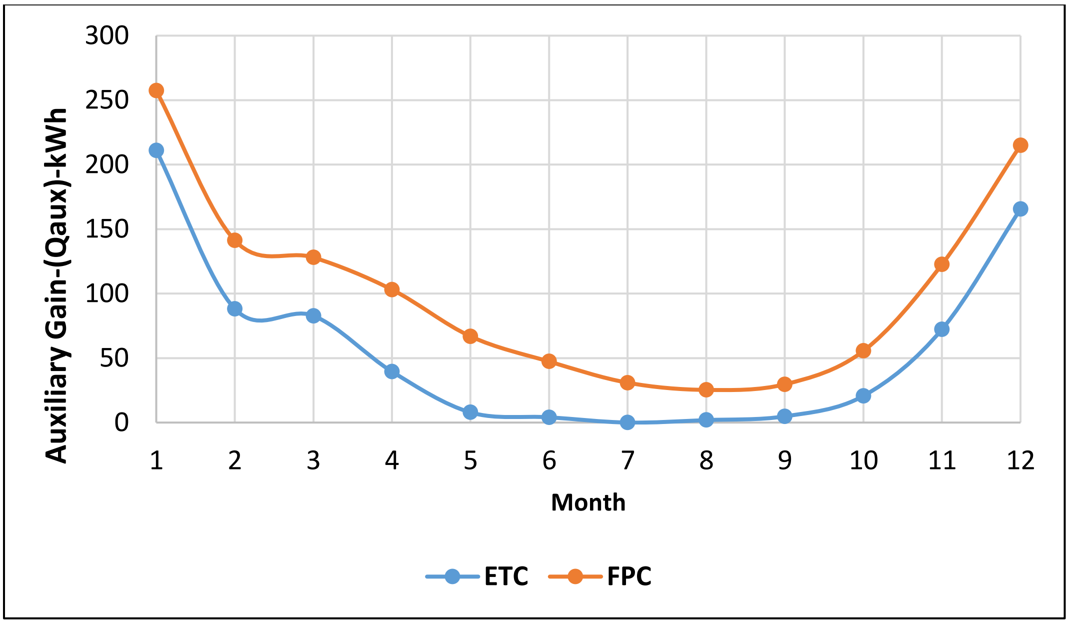

Figure 37: Auxailary Gain (Qaux) kWh (ETC,FPC)

5.1.3 Energy Balance

The energy balance equation is applied for both systems by using equation 1.14 in an excel sheet. The results show well-balanced annual energy assuring the correctness of the simulations and calculations.

It should be considered that not all gains come from solar contribution, but part of the thermal energy needs is compensated by auxiliary heating. This makes the FPC-SDWH system cost more in operation since it needs 524 kWh more thermal energy (from the auxiliary heating unit) than the ETC- SDWH system to satisfy annual hot water demand. Energy components for both systems are presented in tables 7, 8.

Table 7: Energy Balance for ETC

ENERGY BALANCE - EVACAUTED TUBE COLLECTOR										
Month	DE	Qaux	Qpump	Qload	Tloss	Ploss	Qcoll	Qgains	Qlosses	EB%
Jan	1.34	211.08	50.66	552.43	26.37	16.17	334.60	596.34	596.32	0.00%
Feb	-2.73	88.18	53.43	498.77	35.68	20.67	410.73	552.34	552.39	-0.01%
Mar	13.36	82.79	63.16	552.07	50.34	26.96	496.70	642.64	642.73	-0.01%
Apr	-4.39	39.54	65.62	534.37	47.30	24.67	496.66	601.81	601.95	-0.02%
May	-1.42	7.88	73.59	552.02	56.95	27.10	553.09	634.56	634.66	-0.02%
Jun	5.88	4.09	72.92	534.22	60.97	25.90	549.85	626.86	626.98	-0.02%
Jul	0.93	0.00	77.08	552.03	68.21	24.73	568.71	645.79	645.90	-0.02%
Aug	1.51	1.91	75.85	552.06	73.76	26.06	575.51	653.27	653.38	-0.02%
Sep	-6.86	4.81	67.07	534.22	68.97	25.42	549.77	621.65	621.75	-0.02%
Oct	-3.87	20.64	64.14	552.16	61.40	23.63	548.39	633.17	633.31	-0.02%
Nov	-0.87	72.25	56.90	534.27	40.71	19.05	463.90	593.04	593.15	-0.02%
Dec	-5.08	165.55	52.51	552.46	30.87	16.21	376.41	594.46	594.47	0.00%
Sum	-2.19	698.71	772.91	6501.07	621.53	276.59	5924.30	7395.92	7397.00	-0.01%

Table 8: Energy Balance for FPC

ENERGY BALANCE - FLAT PLAT COLLECTOR										
Month	DE	Qaux	Qpump	Qload	Tloss	Ploss	Qcoll	Qgains	Qlosses	EB%
Jan	0.11	257.36	47.08	552.46	22.01	13.57	283.75	588.19	588.15	0.01%
Feb	-2.40	141.23	50.77	498.63	28.42	16.96	349.62	541.63	541.62	0.00%
Mar	6.01	128.02	58.38	552.67	36.00	20.02	428.26	614.65	614.69	-0.01%
Apr	-0.80	103.09	61.56	534.31	35.22	18.30	422.37	587.03	587.02	0.00%
May	-0.69	66.83	68.08	552.20	40.56	18.99	476.17	611.08	611.06	0.00%
Jun	3.19	47.32	66.40	534.19	40.96	16.74	481.32	595.05	595.08	-0.01%
Jul	0.29	30.89	73.31	552.00	45.17	14.09	507.33	611.53	611.54	0.00%
Aug	1.11	25.30	73.67	552.10	49.63	14.90	518.68	617.65	617.74	-0.02%
Sep	-3.58	29.65	65.79	534.29	46.53	16.03	497.70	593.14	593.27	-0.02%
Oct	-1.35	55.51	62.85	552.14	43.99	16.80	493.13	611.49	611.58	-0.02%
Nov	-0.41	122.59	55.22	534.63	33.24	15.76	405.41	583.22	583.23	0.00%
Dec	-4.33	214.98	50.19	553.54	26.38	13.81	324.28	589.44	589.40	0.01%
Sum	-2.84	1222.78	733.29	6503.17	448.12	195.95	5188.02	7144.09	7144.40	0.00%

5.1.4 Efficiency

The daily and monthly efficiency of both systems was calculated by equations 4.2, 4.3. The ETC system's annual mean efficiency is greater than that of the FPC system on average by 8%, as shown in figures 38, 39. It is therefore concluded that ETC is a more efficient system.

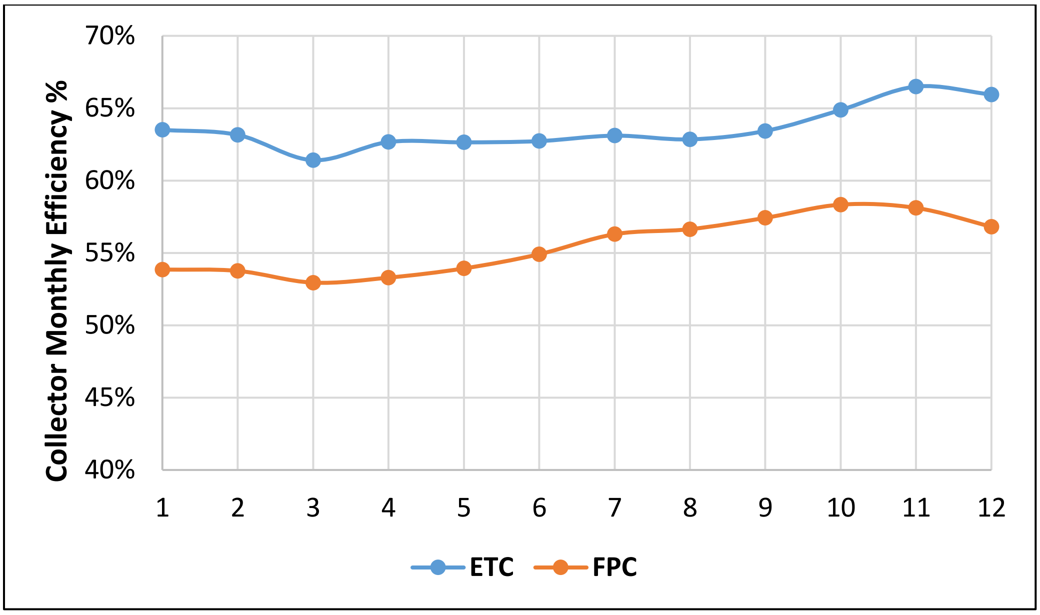

Figure 38:Monthly Efficiency (ETC, FPC)

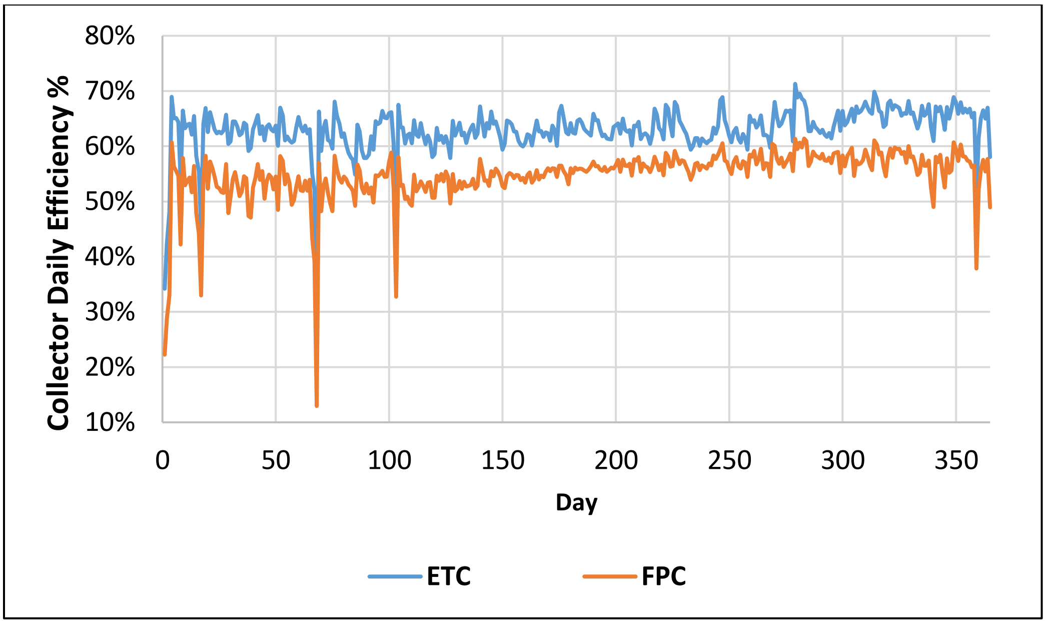

Figure 39: Daily Efficiency (ETC, FPC)

5.2 Result of T*SOL Simulation

The T*SOL simulation focuses on the comparison between two types of SDWH. The first type uses a Flat Plate Collector (FPC), and the second uses Evacuated Tube Collector (ETC). The collector's comparison analysis is performed using the parameters and energy equations listed in the previous chapter (Simulation Methodology T*SOL). The result shows how the energy collected by the collectors how is varying over twelve months. Undoubtedly, the weather fluctuations throughout the year affected the performance of both types of solar collectors. In the end, the system with better performance in Beirut weather conditions will be preferred. Needless to say, that besides all other factors, economic indicators must also be considered when making a decision.

5.2.1 Energy Gains from Collector

It is well known that a solar collector is a device that works on converting solar energy into thermal energy by transferring heat to the circulating water in the system, which is used to heat the water in the storage tank.

The energy gains recorded for this simulation are presented both monthly and annually. The annual energy collected by ETC is 5,014 kWh, and FPC is 4,285 kWh, represented in the following figure 40.

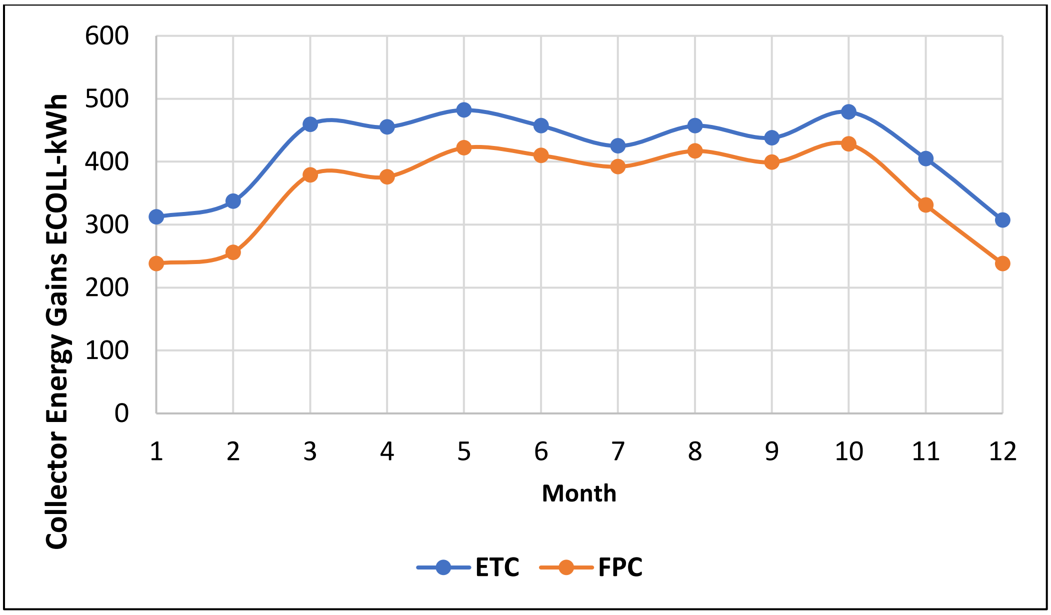

Figure 40: Energy Gains from Collectors - Ecoll

5.2.2 Energy Irradiation on Active Solar Area

The irradiation on the collector is calculated through the radiation strength (W/ m^2) on the collector's tilted surface. Since both collectors ETC and FPC were chosen having approximately the same active area, so the irradiation on both plates is identical as shown in figure 41:

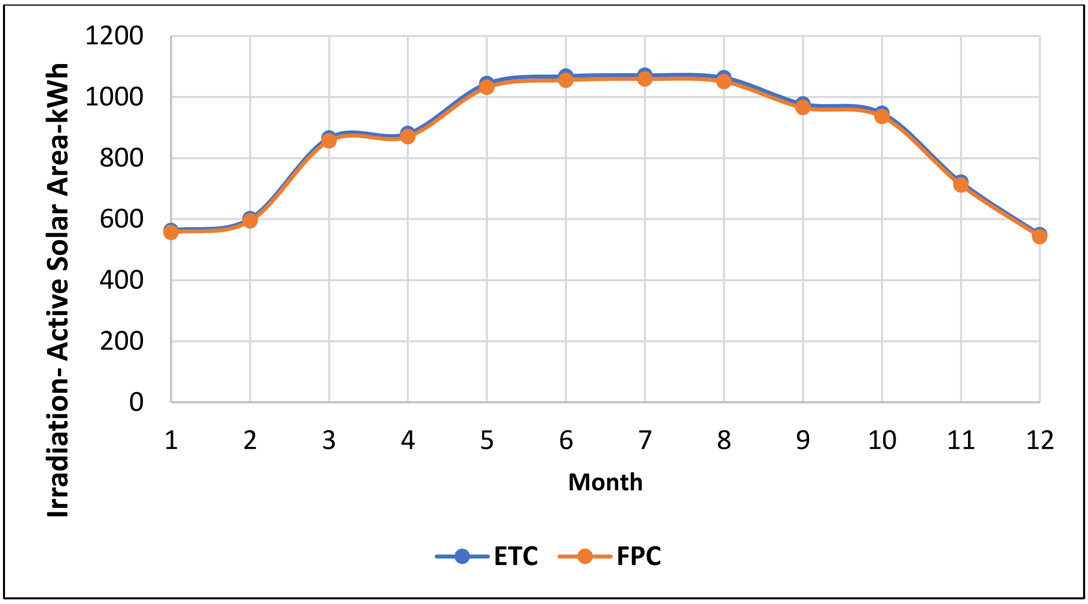

Figure 41: Energy Irradiation on the Active Solar Area

The identical irradiation on the active solar area for both ETC and FPC gives a fair compression when calculating the collector loop efficiency by the following formula: Collector Loop Efficiency = Energy Gains from Collector Loop / Energy Irradiation on Active Solar Area of Collector.

5.2.3 Collector Efficiency

The collector's ratio of energy gains over the energy irradiation on the collector's active area gives the collector efficiency. Thus, the irradiation on the active area of the collector is identical for both plates. The collector who has the biggest energy gains will have the best efficiency. The collector efficiency for both ETC and FPC is calculated using equation 4.7.

The calculated Collector efficiency values are presented in the following tables 9, 10, and figure 42.

Table 9: Evacuated Tube Collector Efficiency

Month	**E - solar loop to tank**	**Irradiation Active Solar Area**	**Collector.Efficiency** = $\frac{\textbf{E − solar loop to tank}}{\textbf{Irradiation active sol}}$
1	312	563	55.4
2	337	601	56
3	459	866	53
4	455	880	51.7
5	482	1044	46.2
6	457	1068	42.8
7	425	1071	39.7
8	457	1063	43.1
9	438	977	44.8
10	479	947	50.6
11	405	721	56.2
12	307	549	55.9
Sum	**5013[kWh]**	**10350[kWh]**	**-**
Mean	**417.75[kWh]**	**862.5[kWh]**	**48.5%**

Table 10: Flat Tube Collector Efficiency

Month	E - solar loop to tank	Irradiation Active Solar Area	Collector.Efficiency = $\frac{E - \text{solar loop to tank}}{\text{Irradiation active sol}}$
1	238	556	42.7
2	256	594	43
3	379	856	44.3
4	376	870	43.2
5	422	1031	40.9
6	410	1055	38.8
7	392	1059	37
8	417	1050	39.7
9	399	965	41.4
10	428	936	45.7
11	331	712	46.5
12	238	543	43.8
Sum	**4286[kWh]**	**10227[kWh]**	**-**
Mean	**357.167[kWh]**	**852.25[kWh]**	**42%**

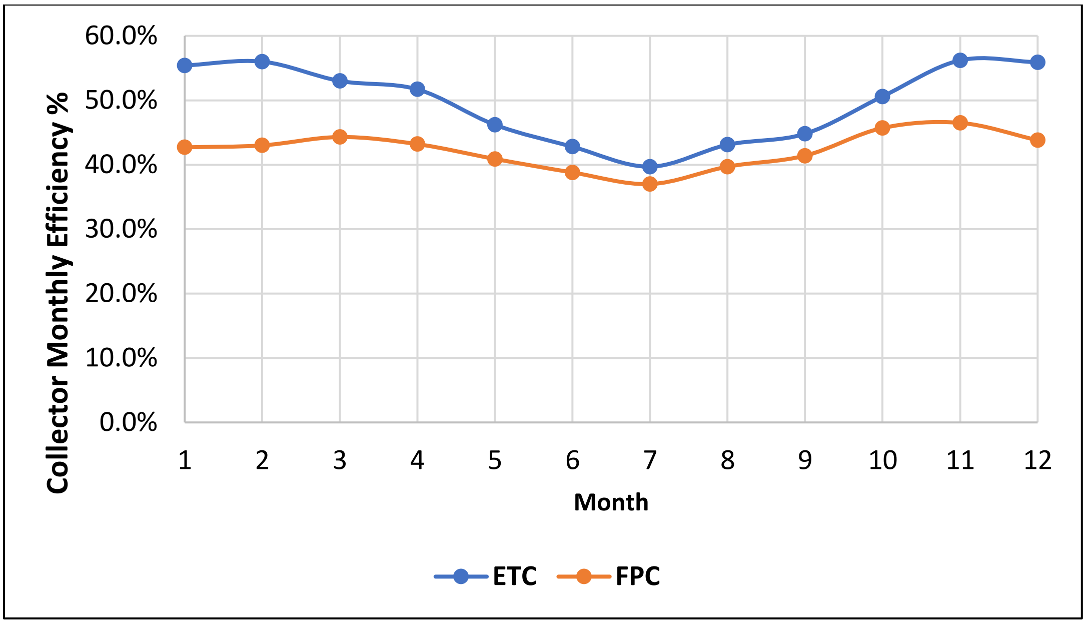

Figure 42: Collector Efficiency (FPC, ETC)

The annual mean efficiency of the FPC is 42.3 %, while it is 49.6 % for ETC. This is a fair test to show that ETC is 7.3 % more efficient than FPC.

5.2.4 Storage Tank Average Temperature

T*SOL simulating program provides the collector temperatures and storage tank temperatures (figure 43). The solar system principle involves the circulation of the heat transfer fluid to transfer the Sun's heat to the water in the storage tank. This process uses a temperature controller that works by comparing the fluid temperature of the collector with the water temperature in the storage tank if:

- $Temp_{Tank} < Temp_{Collector}$ → Pump (ON)
- $Temp_{Tank} > Temp_{Collector}$ → Pump (OFF).

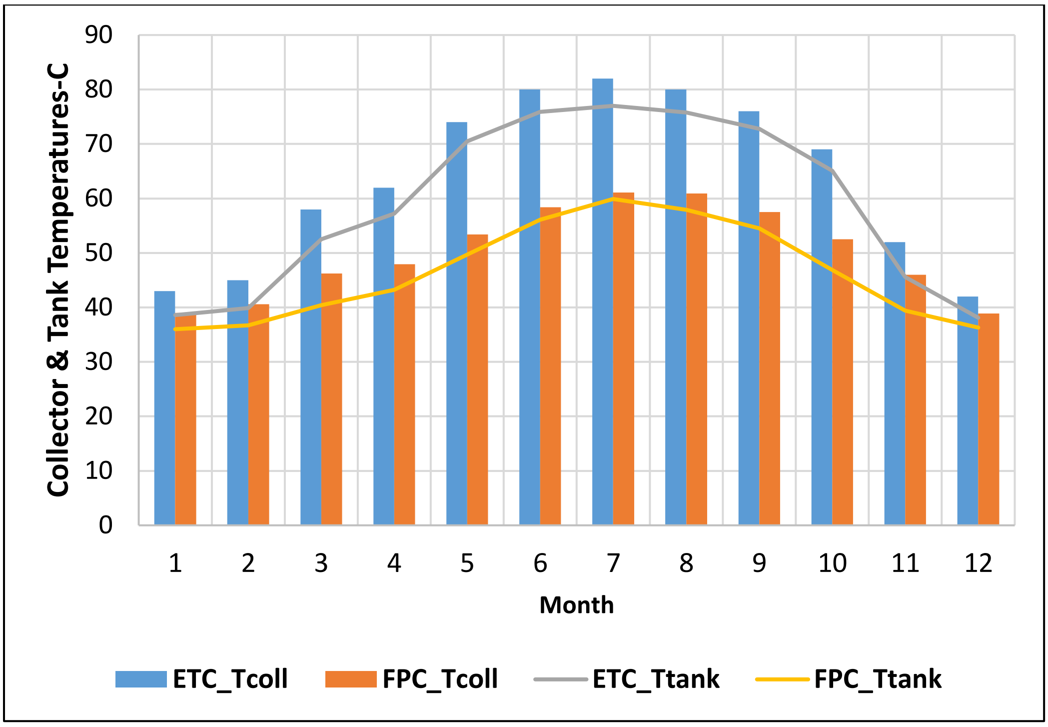

Figure 43: Collector Temperature-T COLL & Tank Avrage Temperature-Tavg

In both systems, is it clear how the mean collector temperature is higher than the water temperature in the storage tank, which means that the system is working fine annually.

5.2.5 The Solar Fraction

The solar fraction is the energy supplied by the solar system divided by the total energy supplied to the storage tank. For no use of solar energy, the solar fraction is zero and One for maximum energy supplied by solar to the device requirement. The solar fractions for both SDWH using ETC and FPC are calculated using equation 4.9.

The Collector Solar Fraction's calculated values are arranged in tables 11 and 12 and graphically presented in figure 44.

Table 11: Evacuated Tube Collector-Solar Fraction

Month	**E - solar loop to tank**	**E Aux heating**	**Solar.Fraction** = $\frac{\textbf{E} - \textbf{solar loop to tank}}{\textbf{E} - \textbf{solar loop to tank} + \textbf{E Aux heating}}$
1	312	180	62
2	337	121	73
3	459	33	92
4	455	21	95
5	482	2	100
6	457	0	100
7	425	0	100
8	457	0	100
9	438	0	100
10	479	2	99
11	405	54	87
12	307	171	64
Sum	**5013[kWh]**	**584[kWh]**	**-**
Mean	**417.75[kWh]**	**48.66[kWh]**	**89%**

Table 12: Flat Plat Collector-Solar Fraction

Month	E - solar loop to tank	E Aux heating	Solar.Fraction = $\frac{\text{E} - \text{solar loop to tank}}{\text{E} - \text{solar loop to tank} + \text{E Aux heating}}$
1	238	257	48
2	256	197	56
3	379	88	81
4	376	72	84
5	422	11	97
6	410	4	99
7	392	0	100
8	417	5	99
9	399	0	100
10	428	17	96
11	331	135	71
12	238	254	48
Sum	**4286[kWh]**	**1040[kWh]**	**-**
Mean	**357.16[kWh]**	**86.67[kWh]**	**80%**

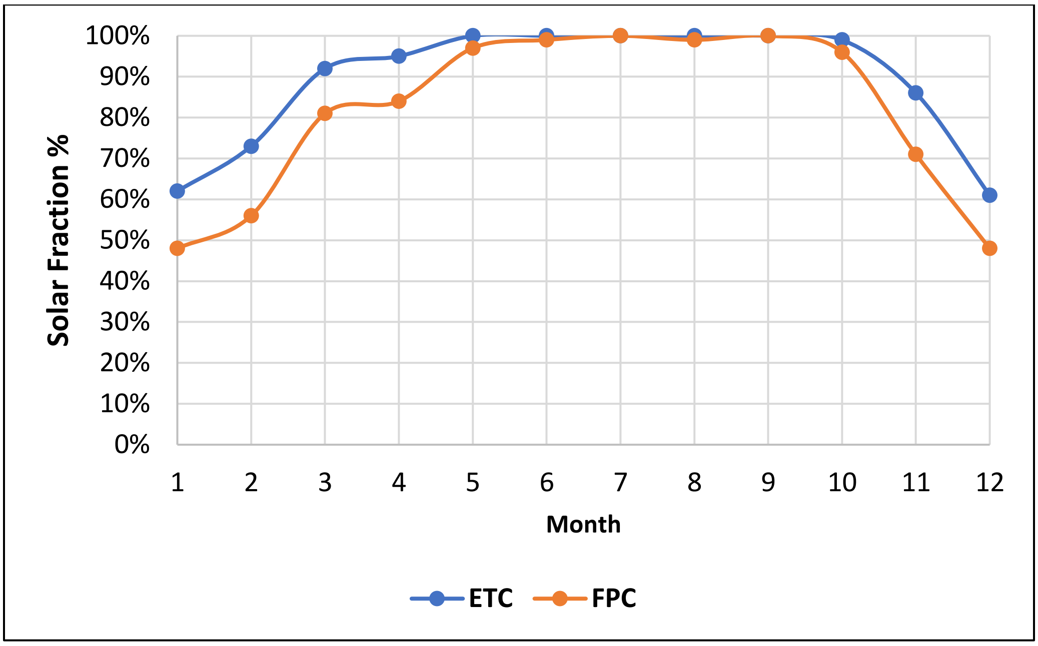

Figure 44: Solar Fraction (FPC, ETC)

The Annual Mean Solar Fraction of the FPC is 80% % while 89% for ETC (figure 44). The Solar Fraction ratio shows that both SDWH systems have a 100 % solar fraction in the summer months. During the rest of the year, both systems require auxiliary heating (figure 45). Again, ETC outperforms FPC and requires 456 kWh less auxiliary heating energy.

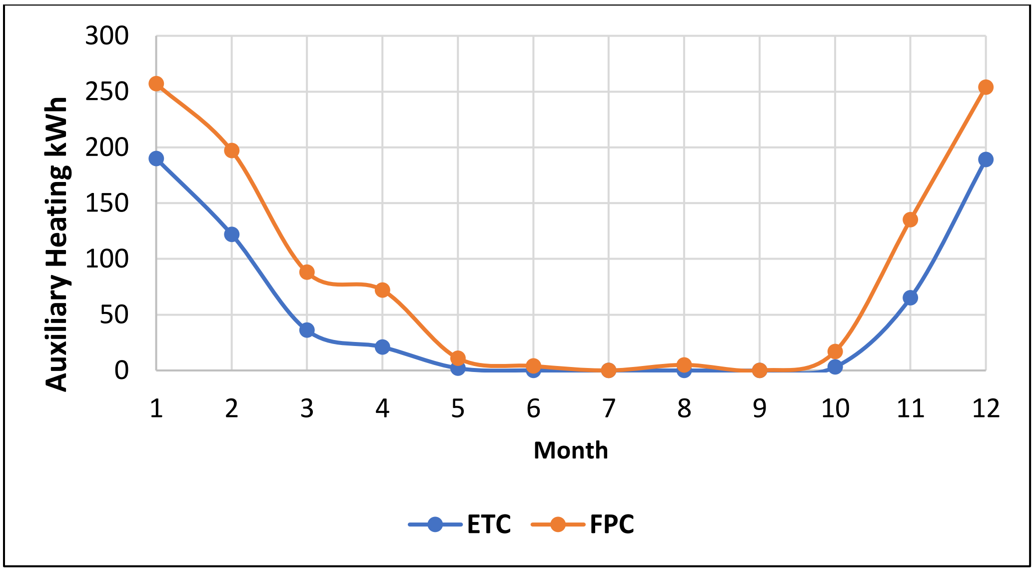

Figure 45: Auxiliary Heating Electricity

5.2.6 Electric Saving

Simply installing solar water heaters makes water heating bills drop. Since solar energy is free, it protects SDWH owners from future fuel shortages and price hikes. The monthly energy savings are presented in figure 46. As seen, the ETC system saves more energy than the FPC system, mostly during the winter, spring, and fall seasons.

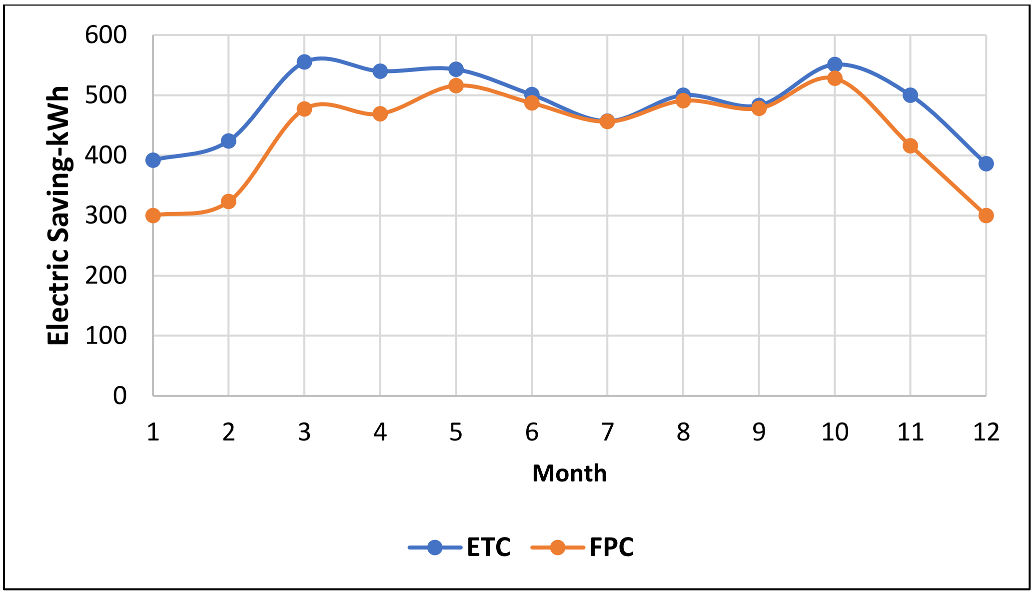

Figure 46: Electric Saving

5.2.7 Calculation of CO_2 Emissions

The CO_2 emissions avoided using the SDWH are computed by calculating the CO_2 emissions of a heating device and emission factors by fuel type used. In T*SOL, the emission factors used if gas was used to generate heat in auxiliary heating. Relevant heating and emission values of natural gas are given in table 13. Monthly CO_2 savings are presented in figure 47.

Table 13: Heating Value and Emissions Factor According to Fuel Type

Fuel	Value of Heating	Factor of emissions
Gas	41100 KJ/m^3	5.14355 g CO_2/kJ

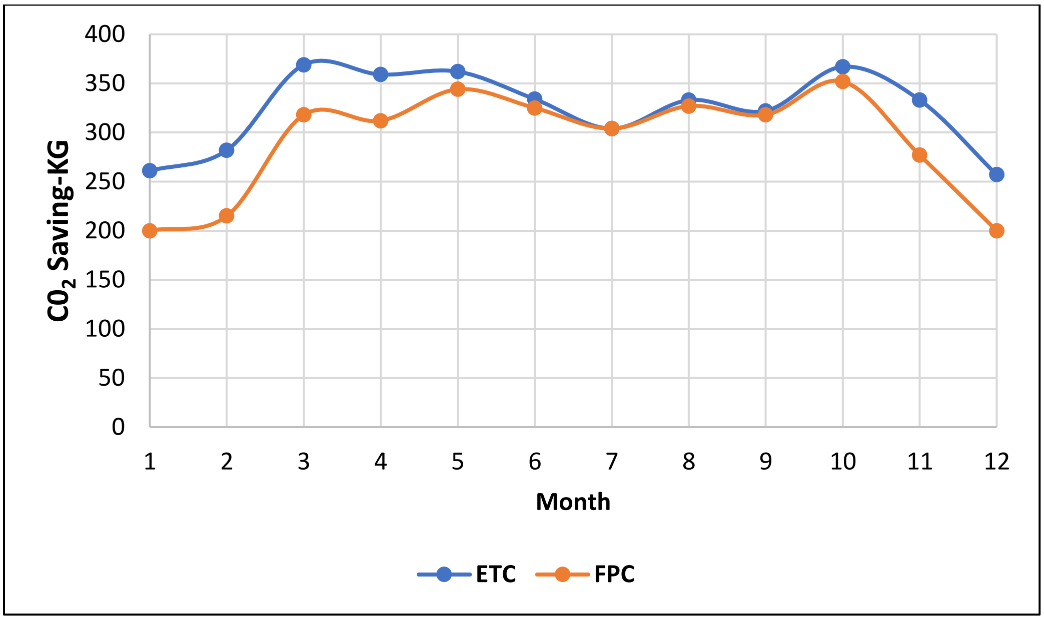

Figure 47: Carbon Dioxide Saving

Since the SDWH system with ETC needs less auxiliary heating, this surely makes it a system with a more CO_2-saving system than the SDWH system with FPC (figure 47).

5.2.8 Calculating the SDWH Efficiency

The efficiency of both SDWH system using ETC and FPC is calculated using equation 4.8.

The efficiency results are presented in tables 14 and 15 and figure 48.

Table 14: Evacuated Tube Collector-System Efficiency

Month	E - solar Domestic Hot Water	Irradiation Active Solar Area	System.Efficiency = $\frac{\text{E} - \text{Solar Domestic Hot water}}{\text{Irradiation active sol}}$
1	305	563	54.2
2	330	601	55
3	433	866	50
4	421	880	47.8
5	424	1044	40.6
6	391	1068	36.6
7	357	1071	33.3
8	390	1063	36.7
9	377	977	38.6
10	429	947	45.3
11	390	721	54.1
12	301	549	54.8
Sum	**4548[kWh]**	**10350 [kWh]**	**-**
Mean	**379[kWh]**	**862.5[kWh]**	**44%**

Table 15: Flat Plat Collector-System Efficiency

Month	E - solar Domestic Hot Water	Irradiation Active Solar Area	System.Efficiency = $\frac{\text{E} - \text{solar loop to tank}}{\text{Irradiation active sol}}$
1	234	556	42.7
2	252	594	43
3	371	856	44.3
4	366	870	43.2
5	403	1031	40.9
6	380	1055	38.8
7	355	1059	37
8	382	1050	39.7
9	372	965	41.4
10	412	936	45.7
11	325	712	46.5
12	234	543	43.8
Sum	**4090[kWh]**	**10227[kWh]**	**-**
Mean	**340.84[kWh]**	**852.25[kWh]**	**40%**

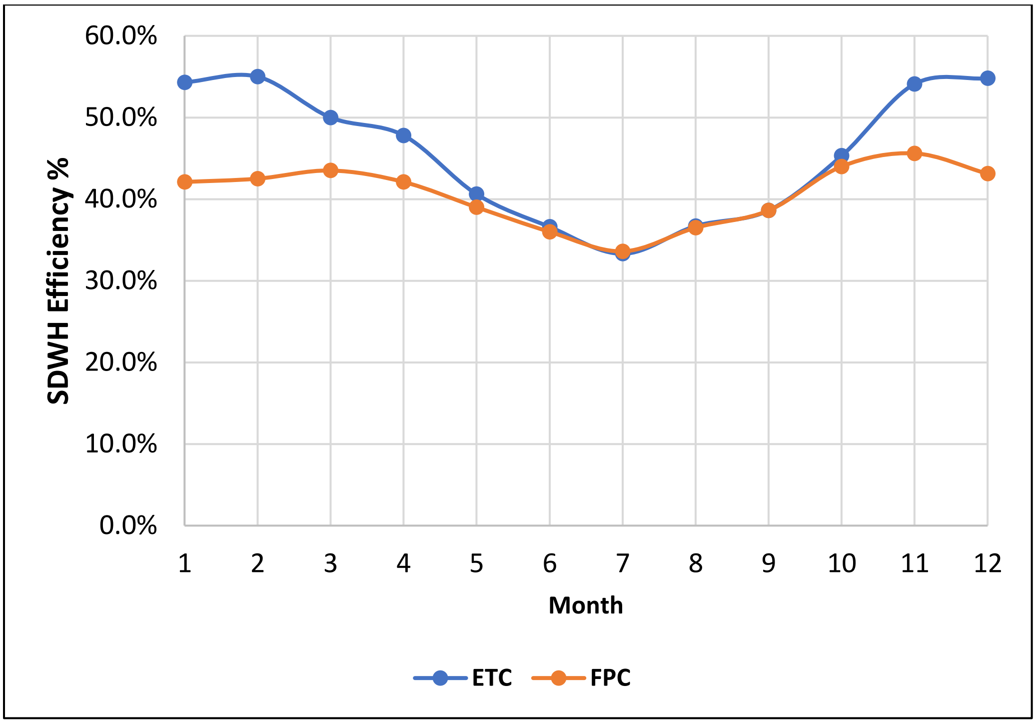

Figure 48: SDWH System Efficiency (ETC,FPC)

As shown in figure 48, the SDWH system's efficiency using ETC is more than the SDWH system using FPC, by 4% points on the annual average. However, in the winter season efficiency of SDWH using ETC is about 10% points higher than the system with FPC.

Chapter 6

ECONOMIC FEASIBILITY

6.1 Economic feasibility study of SDWH Systems

In the following paragraphs, the economic feasibility study of solar water heaters between the two SDWH systems using ETC and FPC is presented. The economic feasibility study is based on the T*SOL simulation thermal results because it uses real collector specifications.

The simulation results showed that: The solar thermal energy produced by the SDWH systems is: 4548 kWh (thermal energy), equivalent to 5824 kWh (electric energy) by using evacuated tube collector type: OPC 15. While the system using flat plate collector type: KSC-AE/ 200/ S produces 4090 kWh (thermal energy) equivalent to 5240 kWh (electric energy). The all-electric water heating system's total energy consumption is 5130 kWh (thermal energy) and 6574 kWh (electric energy).

The savings that can be achieved in using a solar water heater benefit from the cost of annual thermal energy produced by the solar system. The solar system's savings-to-investment ratio (SIR) results from dividing Solar Annual Savings by Solar Life Cycle Investments. If SIR> 1, then the investment is feasible. The Net Present Value (NPV) results from subtracting Solar Annual Savings - Solar Life Cycle Investments.

The economic feasibility study for energy systems is estimated according to the following equations:

Solar system cost can be estimated using the equation:

$$C = C_{solar} * A_c \tag{6.1}$$

- C = Solar water heater system cost $
- C_{solar} = per-unit-area cost 1000 $ / m^2
- A_c = area of collectors 5.1 m^2

The annual energy savings (electricity in this example) can be estimated using the following equation:

$$E_{saving} = \frac{S_{Energy}}{\eta_{Boiler}} \tag{6.2}$$

- E_{saving} = Annual energy saving [kWh/yr.]
- S_{Energy}= Solar energy contribution in heating [kWh/yr.]
- η_{Boiler} = Auxiliary heater efficiency 78%

The annual cost saving is calculated by:

$$S = E_{saving} * C_e \tag{6.3}$$

- S = annual cost saving [$/yr]
- C_e = Cost of auxiliary energy [$/kWh]
- E_{saving} = Annual energy saving [kWh/yr.]

The Net-Present-Value is calculated using the following equation:

(NPV) = present value of savings - present value of investments (6.4)

The savings-to-investment ratio is calculated using the following equation:

$$(SIR) = \text{present value of savings} / \text{present value of investments} \quad (6.5)$$

The calculated values by equations 6.1, 6.2 & 6.3 are presented in tables 16,17,18,19 & 20.

Calculating the SDWH system cost using (equation 6.1):

Table 16: SDWH System Cost

Collector Type	Solar system cost $= \mathbf{C}$	Cost per unit area $= \boldsymbol{C_{solar}}$	Area of collectors $= \boldsymbol{A_c}$
FPC	5100 $	1000 $ / m^2	5.1 m^2
ETC	5160 $	1000 $ / m^2	5.16 m^2

In the old system, electric heater electric energy consumption is calculated from thermal energy consumption, knowing that the boiler efficiency represented in T*SOL is 78%. The software considers the aging of the electric boiler, thus not evaluating its efficacy 100%.

Table 17: Old System Thermal and Electric Consumption

Old System	Electric Heater Thermal Energy Consumption	η_{Boiler}	Electric Heater Electric Energy Consumption
Electric Water Heating System	5130 kWh	0.78 %	6574 kWh

In the new system, the auxiliary electric heater electric energy consumption is calculated from the thermal energy consumption knowing that the boiler efficiency is 78% for the reasons listed previously.

Table 18: New System Thermal and Electric Consumption

New System	Auxiliary Thermal Energy Consumption	η_{Boiler}	Auxiliary Electric Energy Consumption
FPC	1040 kWh	0.78 %	1334 kWh
ETC	583 kWh	0.78 %	748 kWh

Calculating the annual energy saving using (equation 6.2):

Table 19: Annual Energy-Saving Calculation

Collector Type	Old System Thermal Consumption	New System Thermal Consumption	(Old - New) = S_{Energy}	η_{Boiler}	(Old - New) $=E_{saving}$
FPC	5130 kWh	1040 kWh	4090 kWh	0.78 %	5240 kWh
ETC	5130 kWh	583 kWh	4547 kWh	0.78 %	5824 kWh

Calculating annual money-saving using (equation 6.3):

Table 20: Annual Money-Saving Calculation

Collector Type	Old System Electric Consumption	New System Electric Consumption	Energy Saving (Old - New) $= E_{saving}$	Electric Energy Cost $= C_e$	Annual Saving = S
FPC	6574 kWh	1334 kWh	5240 kWh	0.5 $/ kWh	2,620 $/yr.
ETC	6574 kWh	749 kWh	5824 kWh	0.5 $/ kWh	2,912 $/yr.

6.1.1 Economic feasibility study of SDWH system using FPC

The economic feasibility study of the SDWH system using FPC is set according to the data calculated in tables 16,17,18,19 & 20 and listed in the following:

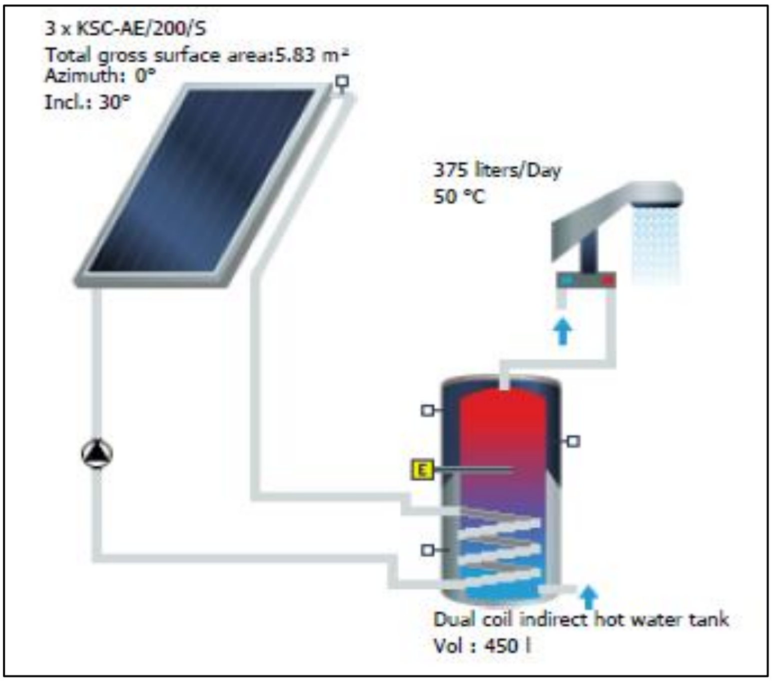

Figure 49: SDWH Using FPC Schematic (T*SOL Software)

➢ Data List:

- SDWH system using (FPC) cost = 5100 $
- Loan Term 5 years, 0 % Interest – Annual Instalment: 1020 $
- Old system heating using only Electric Heater: 6574 kWh
- New system heating Electric Auxiliary Heater: 1334 kWh
- Annual Saving = Old System – New System = 5240 kWh
- Electric energy cost 0.5 $/ kWh
- Money saving: Electric energy saving x 0.5 $/ kWh = 5240 * 0.5 = 2,620 $
- The maintenance cost of the system = 200 $, every four years
- PV Annual Savings: Annual Saving / (1 + Discount Rate)^{Year} , Discount Rate = 2%
- Sum of cash flow = Total savings in (20-year period)
- The total energy consumption 4,090 kWh, where the solar contribution is 5,130 kWh (Figure 50).

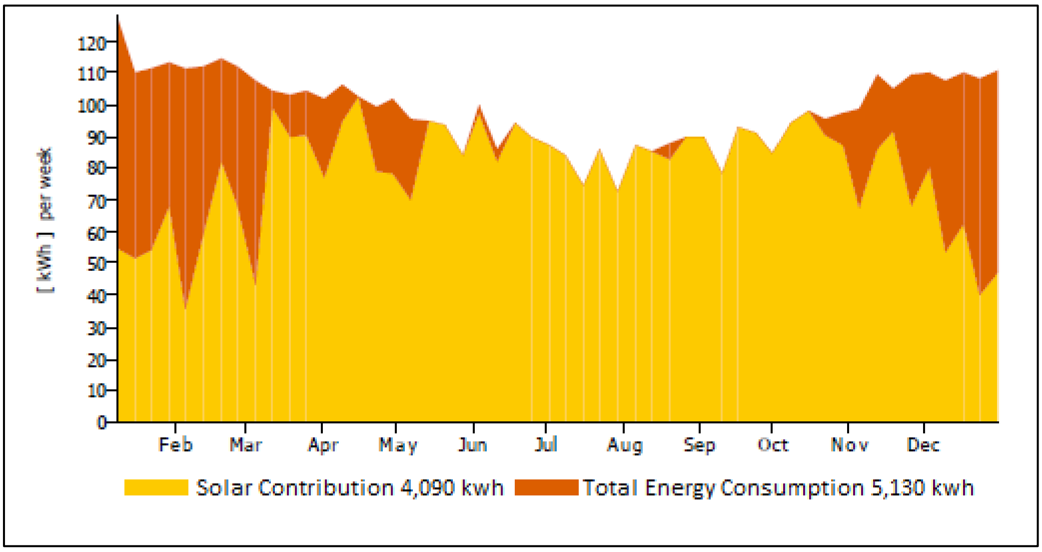

Figure 50: FPC- Solar Energy Total Consumption Percentage

In the following table 21, the economic feasibility study calculation of the SDWH system using FPC is arranged for 20 years period according to the above-listed data of the system:

Table 21: FPC - SDWH Economic Feasibility Calculation

Year	Old system	New System	Annual Saving	PV Annual Saving	Maintenance	Loan capital	Cashflow
				1		-2	(1)-(2)
0	$ -	$ -	$ -	$ -	$ -	$ -	$ -
1	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,568.63	$ -	$ 1,020.00	$ 1,548.63
2	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,518.26	$ -	$ 1,020.00	$ 1,498.26
3	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,468.88	$ -	$ 1,020.00	$ 1,448.88
4	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,420.48	$ 200.00	$ 1,020.00	$ 1,200.48
5	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,373.01	$ -	$ 1,020.00	$ 1,353.01
6	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,326.49	$ -	$ -	$ 2,326.49
7	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,280.87	$ -	$ -	$ 2,280.87
8	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,236.14	$ 200.00	$ -	$ 2,036.14
9	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,192.30	$ -	$ -	$ 2,192.30
10	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,149.31	$ -	$ -	$ 2,149.31
11	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,107.17	$ -	$ -	$ 2,107.17
12	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,065.85	$ 200.00	$ -	$ 1,865.85
13	$ 3,286.00	$ 666.00	$ 2,620.00	$ 2,025.35	$ -	$ -	$ 2,025.35
14	$ 3,286.00	$ 666.00	$ 2,620.00	$ 1,985.63	$ -	$ -	$ 1,985.63
15	$ 3,286.00	$ 666.00	$ 2,620.00	$ 1,946.70	$ -	$ -	$ 1,946.70
16	$ 3,286.00	$ 666.00	$ 2,620.00	$ 1,908.53	$ 200.00	$ -	$ 1,708.53
17	$ 3,286.00	$ 666.00	$ 2,620.00	$ 1,871.11	$ -	$ -	$ 1,871.11
18	$ 3,286.00	$ 666.00	$ 2,620.00	$ 1,834.42	$ -	$ -	$ 1,834.42
19	$ 3,286.00	$ 666.00	$ 2,620.00	$ 1,798.45	$ -	$ -	$ 1,798.45
20	$ 3,286.00	$ 666.00	$ 2,620.00	$ 1,763.18	$ 200.00	$ -	$ 1,563.18
Total	$ 65,720.00	$ 13,320.00	$ 52,400.00	$ 42,840.76	$ 1,000.00	$ 5,100.00	$36,740.76

- Total PV Annual Saving = 42,840 $
- (NPV) = Total PV Annual Saving – (Investment Cost + Maintenance Cost) = 42,840 $ - (5100$ + 1000$) = 36,740 $
- (SIR) = Total PV Annual Saving / (Investment Cost + Maintenance Cost) = 42,840 $ / (5100$ + 1000$) = 7
- Cost of solar energy = Sum of costs over life time / Sum of solar energy produced = (5100$ + 1000$) / (5240 kWh * 20 years) = 0.058 $/kWh.

6.1.2 Economic feasibility study of “SDWH” system using ETC

The economic feasibility study of “SDWH” system using ETC is set according the data calculated in tables 15,16,17,18 & 19 and listed in the following:

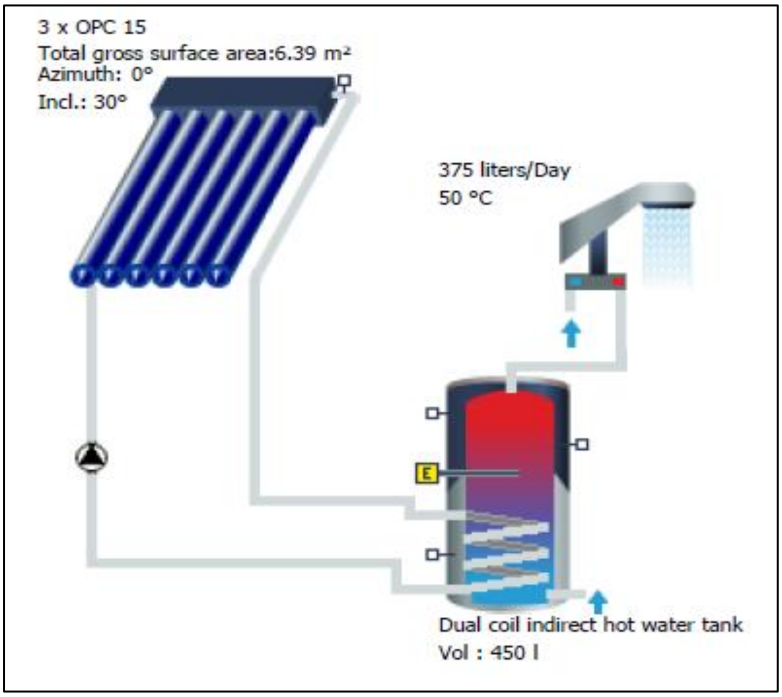

Figure 51: SDWH using ETC Schematic (T*SOL Software)

- Data List:
  - SDWH system using (FPC) cost = 5100 $
  - Loan Term 5 years, 0 % Interest – Annual Instalment: 1020 $
  - Old system heating using only Electric Heater: 6574 kWh
  - New system heating Electric Auxiliary Heater: 749 kWh
  - Annual Saving = Old System – New System = 5824 kWh
  - Electric energy cost 0.5 $/ kWh
  - Money saving: Electric energy saving x 0.5$/ kWh = 5824 * 0.5 = 2,912 $
  - The maintenance cost of the system = 200 $, every four years

- PV Annual Savings: Annual Saving / (1 + Discount Rate)^{Year} ,Discount Rate = 2%
- Sum of cash flow = Total savings in (20-year period)
- The total energy consumption 4,547 kWh, where the solar contribution is 5,130 kWh (Figure 52).

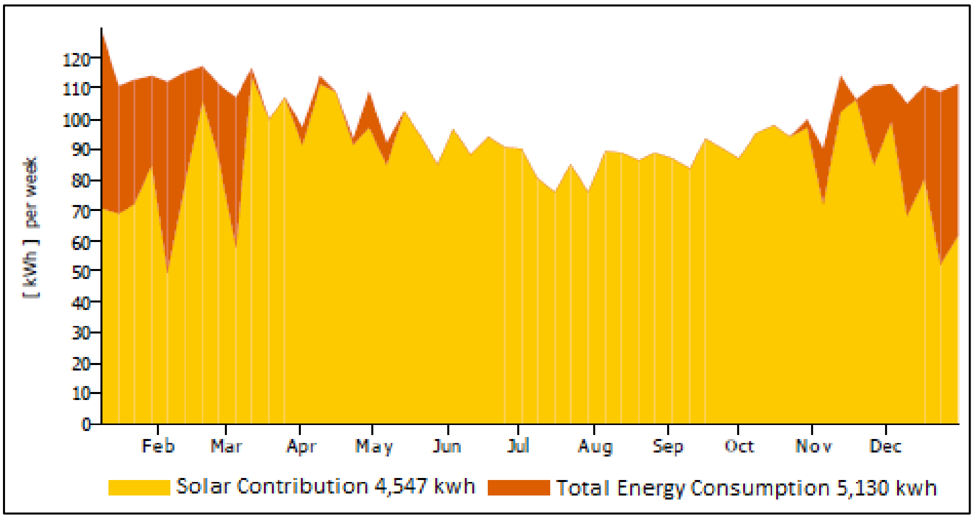

Figure 52: ETC- Solar Energy Total Consumption Percentage

In the following table 22, the economic feasibility study calculation of the SDWH system using ETC is arranged for 20 years period according to the above-listed data of the system:

Table 22: ETC - SDWH Economic Feasibility Calculation

Year	Old system	New System	Annual Saving	PV Annual Saving	Maintenance	Loan capital	Cashflow
				1		-2	(1)-(2)
0	$ -	$ -	$ -	$ -	$ -	$ -	$ -
1	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,854.90	$ -	$ 1,032.00	$ 1,822.90
2	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,798.92	$ -	$ 1,032.00	$ 1,766.92
3	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,744.04	$ -	$ 1,032.00	$ 1,712.04
4	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,690.24	$ 200.00	$ 1,032.00	$ 1,458.24
5	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,637.49	$ -	$ 1,032.00	$ 1,605.49
6	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,585.77	$ -	$ -	$ 2,585.77
7	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,535.07	$ -	$ -	$ 2,535.07
8	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,485.36	$ 200.00	$ -	$ 2,285.36
9	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,436.63	$ -	$ -	$ 2,436.63
10	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,388.85	$ -	$ -	$ 2,388.85
11	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,342.01	$ -	$ -	$ 2,342.01
12	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,296.09	$ 200.00	$ -	$ 2,096.09
13	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,251.07	$ -	$ -	$ 2,251.07
14	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,206.93	$ -	$ -	$ 2,206.93
15	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,163.66	$ -	$ -	$ 2,163.66
16	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,121.23	$ 200.00	$ -	$ 1,921.23
17	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,079.64	$ -	$ -	$ 2,079.64
18	$ 3,286.00	$ 374.00	$ 2,912.00	$ 2,038.86	$ -	$ -	$ 2,038.86
19	$ 3,286.00	$ 374.00	$ 2,912.00	$ 1,998.89	$ -	$ -	$ 1,998.89
20	$ 3,286.00	$ 374.00	$ 2,912.00	$ 1,959.69	$ 200.00	$ -	$ 1,759.69
Total	$ 65,720.00	$ 7,480.00	$ 58,240.00	$ 47,615.37	$ 1,000.00	$ 5,160.00	$41,455.37

- Total PV Annual Saving = 47,615 $
- (NPV) = Total PV Annual Saving – (Investment Cost + Maintenance Cost) = 47,615 $ - (5160$ + 1000$) = 41,455 $
- (SIR) = Total PV Annual Saving / (Investment Cost+ Maintenance Cost) = 47,615 $ / (5160$ + 1000$) = 7.7
- Cost of solar energy = Sum of costs over life time / Sum of solar energy produced = (5100$ + 1000$) / (5824 kWh * 20 years) = 0.052 $/kWh

Arranging the calculated solar energy cost (NPV) & (SIR) of the SDWH of both Systems FPC & ETC:

Table 23: Total Savings, Solar Energy Cost, (NPV) & (SIR)

Collector Type	Total Savings	Cost of Solar Energy	(NPV)	(SIR)	Feasibility
FPC	42,840 $	0.058 $/kWh	36,740 $	7	YES
ETC	47,615 $	0.052 $/kWh	41,455 $	7.7	YES

6.1.3 Summary of SDWH System Economic Feasibility Study

The study made on ETC and FPC SDWH systems having approximately equal investment cost and an identical gross area of the plates studied on the same parameters under the same weather conditions over 20 years showed the cash flow (tables 20,21) of the two systems. The results showed the ETC system type: OPC15 total savings was 47,615 $ while total cash flow for FPC system type KSC-AE/ 200/ S: was 42,840 $, after adding the savings and subtracting the operation cost using money value discount rate of 2% and maintenance coast. FPC: cost of solar energy is 0.058 $/kWh, the (NPV) = 36,740 $ > 0, the (SIR) = 7, ETC: cost of solar energy is 0.052 $/kWh, the (NPV) = 41,455 $ > 0 and the (SIR) = 7.7 this means that both systems are feasible however, the ETC was more feasible having the greatest (SIR) and (NPV) obtaining more savings.

Chapter 7

CONCLUSION

7.1 Summary of the Results

A thermal performance study carried out by TRNSYS simulation software for SDWH systems using ETC and FPC showed that ETC system efficiency is 8 points more than the system efficiency of the FPC. This indicates that ETC has the largest energy gains and, therefore, less requirement for auxiliary heating.

T*SOL simulation results were similar, confirming the TRNSYS simulation results. ETC system has proven to be a more efficient system than the FPC system, particularly during the winter season by having 10 points more system efficiency than FPC. It also had 9 points more annual solar fraction than FPC. This gave the ETC system an advantage to be more self-dependent, thus having less carbon emission due to less reliance on auxiliary heating.

Economic feasibility study performed based on T*SOL simulation results. Results showed that for the ETC system type of OPC15, total savings are $ 47,615 and saving-to-investment ratio is 7.7. On the other hand, the total cash flow for the FPC system type of KSC-AE/ 200/ S is $ 42,840, whereas saving-to-investment ratio is 7. This means that both systems are feasible. However, the ETC is more feasible, having the largest SIR and more life cycle cost savings. This made installing the SDWH system using ETC a more effective and profitable investment for an owner living in Beirut city.

7.2 Conclusions Drawn from This Work

SDWH are proven to be efficient systems when working under Mediterranean climate conditions. The system is also proven to be economically feasible in Lebanon, where the cost of the electricity coming from the utility is high and not reliable.

Thus, before a person owns these systems, she/he should ask herself/himself the followings:

1. Do I live in a place where there is a lot of sunlight during the year? This system depends on direct sunlight, because solar panels must receive enough sun rays to heat the water to heat the water, and the area in which a person lives. Some areas of the world do not receive sunlight most days of the month, so it is not appropriate for such places.
2. Is the cost of installing a solar heater versus the cost of heating water by other means (gas or electricity) worthwhile? The person planning to install such systems should analyze to find out the cost she/he pays monthly for hot water throughout the year, and s/he should compare that value to the cost of installing a solar heater.
3. Do I have enough space in a sunny place to put the solar panels? There is a need for about five square meters of south-facing surface area to receive direct sunlight for the main part of the day.
4. Are the extensions in my home equipped to install the solar heater? The house's piping system must be pre-prepared and configured to install and extend special pipes for the solar heater.

7.3 Suggestions

Based on the great importance of renewable energy technologies, and in line with the global interest in them, and the economic and environmental advantages they achieve, researchers recommend at present the following:

1- The incorporation of renewable energies into the energy policy and the adoption of the general scheme for the investment of renewable energies as a basis for that.

2- The necessity to give adequate attention to the improving energy efficiency in all economic sectors, and developing the use of renewable energy in the country.

3- The need to encourage the establishment of local industries for renewable energy technologies by the joint and private sectors, by providing the necessary facilities, such as exempting local manufacturers from taxation, and exempting the import of production requirements.

4- The necessity of creating cooperation programs and concluding contracts between various ministries of the state, and the private sector to implement joint projects to localize renewable energy technologies.

5- Developing a constructive plan that includes executive mechanisms to encourage citizens to use solar energy for heating and water heating purposes since electricity prices do not remain stable.

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