EVALUATING THE PERFORMANCE OF SOLAR WATER HEATERS IN NAIROBI COUNTY, KENYA

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Evaluating the performance of solar water heaters in Nairobi County, Kenya

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DECLARATION

This is my original work and has not been presented for the award of a degree in any university.

Signature…………….……….……............. Date...…………………………………….

Gilbert Kiplimo Serem

This thesis has been presented for examination with our approval as the University Supervisors.

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DEDICATION

I dedicate this work to my wife who supported and stood by me during this research.

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LIST OF ABBREVIATIONS

AC	Alternating Current
CPC	Compound Parabolic Collector
DHW	Domestic Hot Water
DC	Direct Current
ERC	Energy Regulatory Commission
ETC	Evacuated Tube Collector
FPC	Flat Plate Collector
GoK	Government of Kenya
GW	Giga watts
ICS	Integrated Collector Stores
IMF	International Monetary Fund
IRENA	International Renewable Energy Agency
KPLC	Kenya Power and Lighting Company
LPG	Liquefied Petroleum Gas
MENA	Middle East and North Africa
NPV	Net Present Value
PCM	Phase Change Material
TOE	Tonnes of Oil Equivalent
PV	Photovoltaic
SREP	Scaling up renewable energy program
SWH	Solar Water Heater
T-SOL	Thermal solar

DEFINITION OF TERMS

Solar water heating this is the conversion of sunlight into heat for water heating using a solar thermal collector

Overheat protection it is a term used when no hot water has been used for a day or two, the fluid in the collectors and storage can reach high temperatures in all non-drain back systems. When the storage tank in a drain back system reaches its desired temperature, the pump stops ending the heating process and thus preventing the storage tank from overheating

Passive systems it is defined as systems that rely on heat driven convection or heat pipes to circulate the working fluid

Active system systems that use or incorporate one or more pumps to circulate water or heating fluid

Flat plate collector this is a large, shallow box typically mounted on a roof that heats water or working fluid using sun's energy and usually has a metal box with a glass or plastic cover on top and dark colour absorber plate at the bottom

Evacuated tube collector they are flat devices which consist of cylindrical absorbing surfaces or tubes with internal fins installed in an evacuated tube to reduce the convection losses

Solar collector a special energy exchanger converts solar irradiation energy either to the thermal energy of the working fluid in solar thermal applications

ABSTRACT

Kenya is endowed with ample solar energy resources, with annual averages over 5 $kWh/m^2/day$ available throughout the country. Solar domestic water heating technology has become a common application in many countries and is widely used for heating in single or small multi-family homes. During peak periods that is in the mornings and evenings most of electricity is consumed leading to overload. Much of this electricity is used in water heating and cooking. In order to reduce on this consumption then solar water heating has to be used to cater for electricity that could otherwise be used in water heating.The main objective of the study was to evaluate the performance of solar water heating in Nairobi Kenya, the specific objectives are to determine the effect of tilt angle or orientation and collector size on the thermal performance of solar water heaters, to evaluate the effectiveness of the existing solar water heaters and to determine the cost benefit analysis of installed systems. Infrared thermometer was used to measure temperature, Hukseflux pyranometer for insolation measurement and Thermal solar software for analysis of the performance. This study was conducted between May and June and the temperatures were measured between 9.00 and 16.00 hours. For Flat Plate Collectors, the highest temperatures were attained at 2.00 pm and it gave an average temperature of 67^0C and the lowest temperature was at 9.00 am and it gave temperatures of 42^0C for a collector area of $4.6m^2$ and orientation of 45^0. For a collector area of $2.9m^2$ and orientation of 32^0, the highest temperatures was 50^0C at 2.00 pm while the lowest was 26.5^0Cat 9.00 am. ETC's gave the highest average temperature of 90^0Cwhich was attained at 2.00pm and the lowest was 79.5^0C at 9.00 am for a collector area of $6.9m^2$ and collector orientation of 40^0. For a collector area of $2.9m^2$ and orientation of 30^0, the highest average temperature was 68^0Cwhich was attained at 2.00pm and the lowest was 30.4^0C at 9.00 am.The highest solar insolation attained was $6.5kWh/m^2/day$ and the lowest was $3.76kWh/m^2/day$ in May and in June the highest was $6.1kWh/m^2/day$ and lowest was $3.78kWh/m^2/day$. During this study T*SOL software was used to simulation and analysis of annual thermal performance of both FPC and ETC and it gives an overview of operation of these collectors throughout the year.Cost benefit analysis of the SWH systems were done at a price per kWh of KES 12.75 for a consumption of 50 to 1500kWh for May to September 2017. FPC gave payback period of 2 years and changing the price for ETC gave a payback period of 4 years. It is recommended that angles of 45^0 for FPC's and collector area of $4.6m^2$ be considered while ETC's optimum angles recommended is 40^0 collector area of $6.9m^2$.

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Industrial growth over the past Century has seen an ever increasing demand on the earth’s fossil fuel resources such as Coal and oil. These fuels have been favoured due to their ease of extraction and cost effective conversion into usable energy. However recent discussions into the effects of fossil fuels on the environment have encouraged investigation into renewable energy sources as a way of alleviating negative environmental effects. Africa, probably more than any other continent, faces the double challenge of improving the living conditions of its population by dramatically increasing access to modern energy services, while simultaneously developing its energy sector in a way that is sustainable (Janorch, 2011)

Energy is considered one of the best ways in the generation of wealth and a significant factor in economic development. The importance of energy in economic development is recognized universally, and historical data verified that there is a strong relationship between the availability of energy and economic activity. Although in the early seventies, after the oil crises, the concern was on the cost of energy, however during the past two decades, the risk and reality of environmental degradation have become more apparent. A combination of several factors that lead to environmental problems as evidenced is due to the environmental impact of human activities has grown dramatically (Soteris, 2004). Also due to the increase of the world population, energy consumption and industrial activities. In order to achieve solutions to the environmental problems that humanity faces today then it requires long term potential actions for sustainable development. Renewable energy y resources is proving to be one of the most efficient and effective solutions.

Kenya is endowed with ample solar energy resources, with annual averages over 5 $kWh/m^2/day$ available throughout the country. In the northern part of Kenya and along the Lake Victoria basin, solar energy resources are generally higher and more consistent. In the populated areas near Nairobi, Mt Kenya and the Aberdares, solar irradiation is considerably reduced during the cloudy season between May and August (<3.5 kWh/m^2/day) (Hankins *et al*., 2009).

Due to worldwide energy crisis and abundance of renewable energy sources particularly solar energy in the environment, it has become a major energy alternative. Many solar energy uses depends upon type of application, and one of the most common applications of solar energy at low temperatures is heating of water for useful purposes. There are several types of solar water heating system; however, water heating systems are very popular based on the flat plate collectors (FPCs), evacuated tube collectors (ETCs) and compound parabolic collectors (CPCs) while flat plate and evacuated tube are mostly used collectors for residential and other water heating applications (Pandey *et.al.,* 2015).

Solar water heating (SWH) is the conversion of sunlight into renewable energy for water heating using a solar thermal collector. The solar water heating systems use the sun to heat either water or a heat-transfer fluid, such as a water-glycol antifreeze mixture, in collectors generally mounted on a roof. The heated fluid transfers heat to water and is then stored in a tank either at the roof or ground similar to a conventional gas or electric water tank. There are a number of systems that incorporate the use of an electric pump to circulate the fluid through the collectors. Such technology is extremely cost efficient and can generate hot water in any climate. Recently, SHWs have been more commonly implemented to provide useful power. In 2010 SHW implementation capacity increased worldwide by an estimated 25 giga watts-thermal, compared to 2009. This increase is mainly due to the system's long-term performance, which requires relatively little maintenance, and low set-up cost compared to other solar conversion systems (Kazuz, 2014)

Solar domestic water heating technology has become a common application in many countries and is widely used for domestic hot water preparation in single or small multi-family homes. The technology is mature and has been commercially available in many countries for over 30 years (IRENA, 2015).

Solar water heating system (SWHS) supplies hot water at 60°C to 80°C using only solar thermal energy without any other fuel. It has three main components, namely;

Solar Collector, insulated hot water storage tank and cold water tank with required insulated hot water pipelines and accessories.

In the case of smaller systems (100 – 2000 litres per day), the hot water reaches the user end, by natural (thermo – siphon) circulation for which the storage tank is located above the collectors. In higher capacity systems, a pump may be used for forced circulation of water. The hot water with lower density moves upwards and cold water with higher density moves down from the tank due to gravity head. The domestic sector in Kenya consumes approximately 13 % from the total electrical load and about 40% of the reminder is consumed with electric water heating. A well installed solar water heating system may reduce to a large extent domestic electric water heating costs up to 70% if well implemented. However, this enormous environmentally friendly and sustainable energy potential is hardly used due to various reasons linked to the financially related, market-related, legislation-related, technical and awareness barriers imposed towards the spreading of SWH technology (Dintchev, 2004).

Solar water heating (SWH) is a well-proven and readily available technology that directly substitutes renewable energy for conventional water heating. This system has the following benefits which include:-

Hot water throughout the year- The system works all year round as Kenya experiences sunlight throughout the year.

Reduced energy bills-Sunlight is free, so once you've paid for the initial installation your hot water costs was reduced.

Lower carbon footprint-Solar hot water is a green, renewable heating system and can reduce your carbon dioxide emissions.

According to (Kishor *et al.*, 2010) water heating by solar energy for domestic use is one of the most successful and feasible applications of solar energy. Other areas of application of solar energy include solar drying, electricity generation using photovoltaic cells, solar cooling and refrigeration, solar still (or solar distillation) and solar cooking. An ambitious solar plan that would result in the generation of

20,000MW of solar energy by 2022 had been put in place by India (Renewable Energy World, 2010).

Water heating of Kenyan homes normally consumes about approximately between 40 to 50% of our electric power bills. Solar water heaters have been in the past years the easiest and fastest way of slashing electric power bill without having to incur a lot in major investments. Presently, solar powered solutions are in fact the most affordable way to reduce on power consumption. Normally the investment of installed domestic solar system installations is gained back in approximately 1 year and 4 to 5 years for commercial ones from the saving off the power bill. Once installation has been done, the system gives full time and free hot water for many years to come.

Despite the fact that solar water heaters cannot produce 100% of the hot water required throughout the year and sometimes might need to be electrically boosted, they represent a very relevant element for power saving. Kenya is blessed with favourable climate which the systems can utilise to produce up to 90% of the hot water demand in a good-sized system.

The current solar thermal technology and its products has made great progress in the past years putting onto the market more and more reliable, durable and effective solar water heating units. Product designers have also put a lot of effort in improving the esthetical impact of solar water heaters products that are installed on roofs of both domestic and commercial buildings. The heat pipe system is definitely a good example of the effort taken with its clean, modern and technological look, the hidden piping and the attention to details up to the mounting kit.

Using the sun's energy to heat water is not a long known idea (Marshall, 2009). The Romans warmed their baths with large south-facing windows and modern-prototype solar water-heating systems of copper tubes in glass enclosed boxes were already invented by the late 1800s. Solar water heating has been reported to enjoy much popularity in places like Australia, Israel, the United States of America, Germany, Sweden, India, Jordan, Cyprus, China, Greece and Japan (Revees, 2009). By tapping available renewable energy, solar water heating reduces consumption of conventional energy that would otherwise be used. Each unit of energy delivered to heat water with a solar heating system yields an even greater reduction in use of fossil fuels. Water heating by natural gas, propane, or fuel oil is only about 60% efficient and although electric water heating is about 90% efficient, the production of electricity from fossil fuels is generally only 30% or 40% efficient. Reducing fossil fuel use for water heating not only saves stocks of the fossil fuels, but eliminates the air pollution and climate change gas emission associated with burning those fuels. (Sarah *et al.*, 2013)

Solar water heating system is based on a simple natural phenomenon. Cold water in a container exposed to the sun undergoes a rise in temperature. However, this natural temperature gain is usually very low, being only a few degrees Celsius. The reasons for this low temperature gain are due to the low heat absorption of water and because much of the heat that is absorbed goes into increase evaporation, a change of state from liquid to gas phenomenon, thus reducing temperature rise. A solar water heater employs a solar collector with good absorption capacity and with the ability of collecting energy from over a wider area and harnessing the energy collected to raise the water temperature significantly. The issue of evaporation of the working liquid is significantly minimized since the fluid flow is within insulated pipes and storage tank. Solar water heaters, also called solar domestic hot water systems, can therefore be a cost-effective way to generate hot water. They can be used in any climate, and the fuel they use the most, sunshine, is absolutely free (Revees, 2009).

1.2 Energy Demand in Kenya

Energy demand in Kenya may be classified as conventional and traditional. Electricity and fossil fuels are the main commercial energy sources whereas wood-fuel (wood and charcoal) is the dominant energy source in the traditional sector. Urban and rural household energy consumption accounts for the major part of energy consumption in most African countries. It ranges between 50-70 and 58-93 percent in African countries with medium and low income per capita respectively. Satisfying the household energy needs takes up a substantial portion of the income of the urban household, while in the rural areas much time and effort are spent on collecting wood fuel instead of using it on more productive activities. The rural areas depend on wood fuel, agricultural residues and animal wastes for most of their heating and cooking needs whereas the urban households depend on charcoal, Liquefied Petroleum Gas (LPG) and electricity for their cooking and heating needs. Commercial energy consumption in the country accounts for over 40% of the total energy consumption [Ministry of energy GoK, 2012]. Electricity is used in lighting and industrial processes whereas petroleum products are used in boilers for processing steam and electricity generation, while in the transport sector as fuel for internal combustion engines.

Table 1.1: Energy Demand in Kenya by sectors in Tonnes of Oil Equivalent (TOE) (Source: KPLC, 2009)

Sector	Energy Demand	Percentage
Households	4339	59
Commerce	284	3.9
Manufacturing	990	13.5
Transport	1056	14.3
Agriculture	68.2	9.3
Total	**7351**	**100**

The energy demand in Kenya is expected to increase in the future because of the following factors: Expected increase in energy consumption per capita, rural industrialization and electrification, the ambition of Kenya to became industrialized by 2030, expected increase in the peoples living standards and rapid increase in public and private vehicles.

1.3 Statement of the problem

Solar thermal energy is mainly used for drying and water heating. Solar water heaters (SWH) are mainly utilized in households and institutions such as universities, hotels and hospitals. The number of solar water heating units currently in use in Kenya is estimated at over 77,000 (EED, 2017) and is projected to grow to more than 400,000 units by 2020 (SREP, 2011). The uptake level of solar water heating systems in Kenya is extremely low despite the enormous potential provided by the abundant availability of the solar energy resource and the demand for low temperature water for both domestic and commercial applications.

With the country expecting more growth in buildings and constructions, then it means its energy demand will increase and thus generation capacity will be required in order to meet its rapidly growing electricity demand, including during peak hours. Electricity demand in the country is increasing rapidly mainly due to the accelerated productive investment and increasing population.

Solar water heating in Kenya is proving to be a potential way of water heating and therefore evaluating its performance is important and will help reduce dependency on electricity thus encouraging more people to install them. Since most of Kenya's rural and urban families depend on electricity for heating, cooking and lighting then they do incur a huge cost of bills and if they will have a performing solar water heater then it will reduce overreliance on electricity.

1.4 Justification

Kenya experiences a large energy gap between energy demand and supply and most of this energy is from electricity. Kenya has an ever growing population of 43,031,341 as at July 2012 and its economy was growing at a rate of 5.6% by 2010 (IMF, 2012). This has led to an increased energy demand in the country.

Therefore in order to meet its demand then other sources of energy and ways of reducing overreliance on electricity has to be devised. During peak periods that is in the mornings and evenings, most of electricity is consumed leading to overload and much of this electricity is used in water heating and cooking. In order to reduce on these consumption then solar water heating has to be used to cater for electricity that could otherwise be used in water heating. Currently, the residential sector in Kenya consumes up to 850 Gigawatt per hour of electricity annually to heat water causing a strain on the power infrastructure especially during peak times (morning and evening) thereby increasing the overall peak load. This necessitates dispatch of expensive thermal power, which are used as peaking plants (SREP, 2011). Use of solar water heating systems can therefore reduce the peak demand arising from the need for water heating by domestic, institutional and commercial users. It is estimated that households switching to solar can save up to 60% on water bills compared to relying solely on electricity for water heating. Incorporating SWH then will cut cost of electric use.

Due to the existing solar water heating laws from Energy regulatory commission (ERC) which states that all premises within the jurisdiction of local authorities with hot water requirements of a capacity exceeding 100 litres per day shall install and use solar heating systems and also an electric power distributor or supplier shall not provide electricity supply to premises where a solar water heating systems has not been installed in accordance with the Regulations (ERC, 2012). Therefore with such laws then it was a design feature when coming up with structures that one has to have solar water heaters and this is aimed at reducing overreliance on electricity.

With an increasing population in the country then it means there was an increase in buildings construction and therefore ready market for SWH. Due to this then it means more people will need to heat water and since the initial design of most buildings will incorporate SWH then there was need to ensure that there is no overload on the existing electricity demand and also since there is expansion of rural electrification then whatever source of energy we have would not be sufficient and therefore an alternative was to incorporate SWH to heat water thus reducing such overload.

1.5 Research Objectives

1.5.1 Main Objectives

The main objective of this study is to evaluate the performance of solar water heating in Nairobi County, Kenya.

1.5.2 Specific Objectives

The specific objectives are:

1. To determine the effect of orientation and collector size on the thermal performance of solar water heaters.

2. To evaluate the effectiveness of the existing solar water heaters such as flat plate and evacuated tube collectors and compare their efficiencies
3. To conduct the cost benefit analysis of the installed solar water heaters.

CHAPTER TWO

LITERATURE REVIEW

2.1 Solar water heating

2.1.1 Overview

For many years, solar domestic hot water (DHW) systems have gained great attention due to their considerable energy conservation, environmental protection and relatively good economy. Recently, environmental issues have led to an even greater interest in solar DHW systems (Selfa, 2015).

Experiments conducted by (Sivakumar *et al*.,2012) using 9 riser tubes, 12 riser tubes and zig- zag arrangement of riser tubes between 9.00 hours and 17.00 hours. The collector efficiency at 9.00 hour is 36.4% for 9 riser tubes, 39.2% for 12 riser tubes and 42% for zigzag arrangement system. The maximum efficiency is observed at the time 13.00 hour in all the three cases as 53.38%, 59.09%, and 62.90%, respectively. The outlet temperatures at 9.00 hour is 43°C, 44°C and 46°C for 9 riser tubes, 12 riser tubes and zig-zag arrangement respectively. The maximum outlet temperatures were recorded at 13.00 hour for all three cases. The outlet temperature reduced after 13.00 hour until 17.00 hour for all three cases.

The natural circulation solar water heater was tested for 12 days in the month of November by (Bukola, 2006) at intervals of one hour between 8.00 and 18.00 hours. The inlet and outlet temperatures for collector and storage tank as well as ambient temperature were measured with mercury in glass thermometer with 0.5^0C thermometer. From his results he found out that the maximum temperature occurred after the peak solar insolation. During the test a maximum water temperature of 83.5^0C was obtained while the ambient temperature was 34.5^0C. From this it shows the hot water temperature was 49^0C higher than ambient temperature. He also found that the collector efficiency increased with decreasing collector performance coefficient.

SWH systems seem to have a huge prospectus but only a fraction of the projected possible utilization has been realized. As at 2010 as illustrated in Figure 2.1, the total installed capacity of SWH systems and space heating systems was estimated to have increased by an estimated 16%, reaching only about 185 GW of thermal energy globally. According to projections, the energy requirement by the year 2030will be around 0.6% and these means more land will be required for 10% net efficient solar conversion systems. By 2010 over 100 countries had initiated policy targets or promotion incentives related to renewable energy. There has been an increase in the use of solar energy technology to about 30% yearly as from 1980. According to Renewable Energy Policy Network 2010, it has reported that about 70 million houses are now using solar water heating (SWH) systems worldwide. The economic benefits of the utilization of SWH can mainly be realized through savings in fuel costs for water heating and environmental issues (Raisul *et al.*, 2012).

The sun traverses the sky from east to west. The tubular design of evacuated tube collectors means that, so long as they are within 40 degrees of due south, they are always facing the sun and automatically absorbing maximum solar energy.

Comparing the temperatures for both flat plate and vacuum tubes collectors of the same size, it is seen that there is a difference in the recorded values and this is due to the fact that flat plates have a good sun picking characteristic as compared to vacuum tubes making them have higher temperature values than ETC in the morning. On the other hand, the sun has a maximum altitude at noon, and in order to absorb the largest rate of energy at this hour, the collector should be orientated towards the south or at least within 30° of south (Soteris, 2004). To make sure that the collector`s performance is maximized, it should be facing direct sun from 9 a.m. until 3 p.m. During these hours, the solar collector receives close to 80-90 % of the total solar irradiance available through the day (Ramlow & Nusz, 2006).

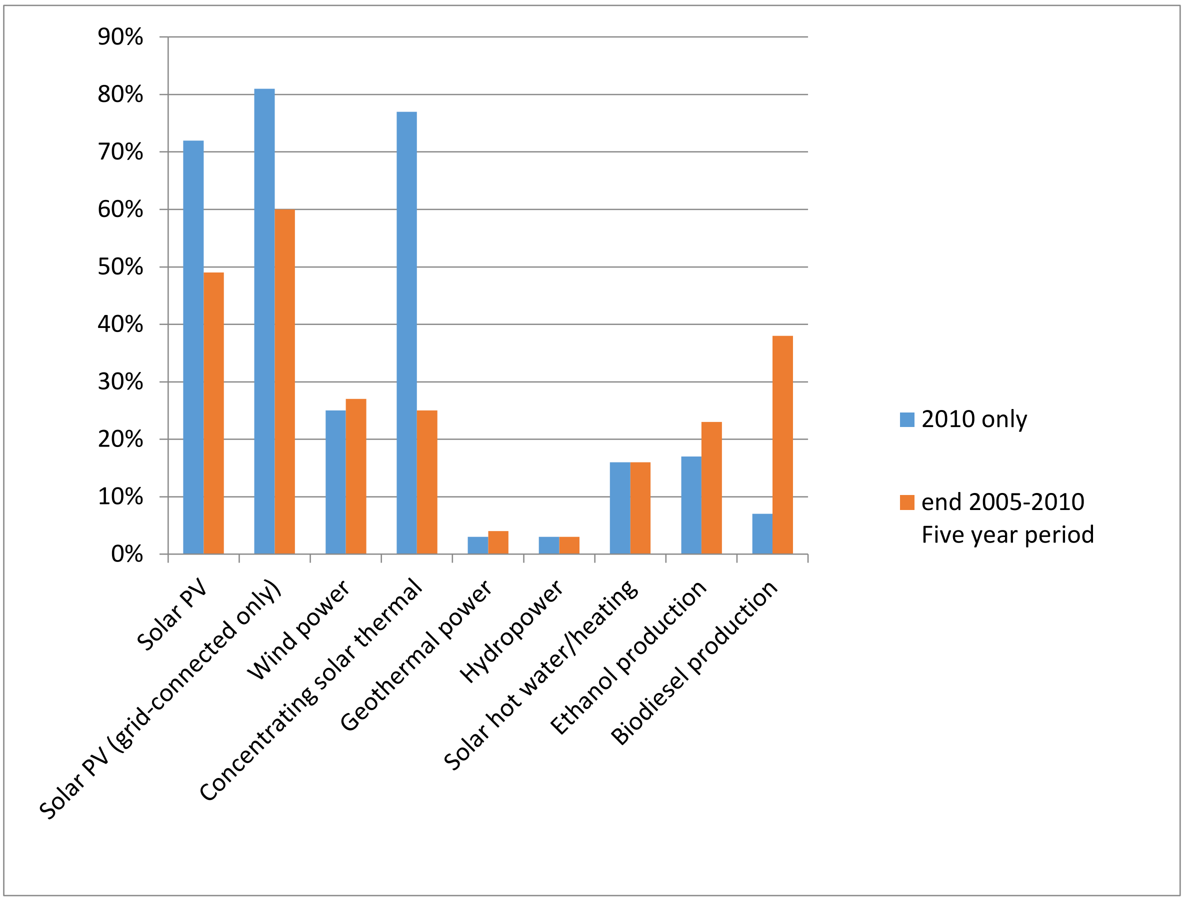

Figure 2.1-Average annual growth rates of renewable energy capacity worldwide, 2005 to 2010(source; Raisul et al., 2012)

In a test performed by (Dinchev, 2004) to evaluate the thermal performance of the SWH with testing time of 8 hours equally spaced about solar noon. Fourteen hot water discharges 15 litres each are made at 10.00 h, 12.00 h, 14.00 h and16.00 h. After that repeatedly 11 x 15 litres discharges are taken until the water temperature is 2^0 C above the ambient temperature.

Efficiency of flat plate collectors ranges between 55-75% with different parameters and also storage temperatures of different collectors ranges from 50^0C – 70^0C. The collector area having a variation of $1.9m^2$ to $2.5m^2$ for given collectors (Sunil *et al.*, 2013)

A solar hot water system (SHW) is a conversion tool, which transforms sunlight into heat to produce hot water. Solar water heating technology has been employed for many years because it is the easiest and more economical way to use since the sun saves energy and money. One of the earliest documented cases of solar energy use involved pioneers moving west after the Civil War. They would place a cooking pot filled with cold water in the sun all day to have heated water in the evening. The first solar water heater that resembles the concept still in use today was a metal tank that was painted black and placed on the roof where it was tilted toward the sun. The concept worked, but it usually took all day for the water to heat, then, as soon as the sun went down, it cooled off quickly because the tank was not insulated (Christopher, 2009).

In an analysis performed by (Soteris, 2004) on the environmental problems related to the use of conventional sources of energy and the benefits offered by renewable energy systems. The various types of collectors including flat-plate, compound parabolic, evacuated tube, parabolic trough, Fresnel lens, parabolic dish and heliostat field collectors were used. The thermal performance of the solar collector was determined by obtaining values of instantaneous efficiency for different combinations of incident radiation, ambient temperature, and inlet fluid temperature.

In order to heat water using solar energy, a collector, that is often fastened or placed to a roof or a wall facing the sun’s direction, heats a working fluid that is either pumped (active system) or driven by natural convection (passive system) through it. The collector could be made of a simple glass-topped insulated box with a flat solar absorber made of sheet metal, attached to copper heat exchanger pipes and dark-colored, or a set of metal tubes surrounded by an evacuated (near vacuum) glass cylinder.

Experiments conducted by (Arekete, 2013) on solar water heater performance was tested for a period of six days. Hourly readings of the ambient, inlet and outlet temperatures and radiation intensity were recorded between 9.00hrs and 16.00 hrs. Between the hours of 12.00 and 4.00 pm, hot water temperatures of above 50^0C were achieved. The maximum hot water temperature recorded was 73^0C and the mean peak hot water temperature was 70^0C.

The thermal performance of a solar water heating system with 4 m^2 flat plate collectors in Dublin, Ireland was conducted by (Duffy and Ayompe, 2013). The experimental setup consisted of a commercially available forced circulation domestic scale system fitted with an automated sub-system that controlled hot water draw offs and the operation of an auxiliary immersion heater. The system was tested over a year and the maximum recorded collector outlet fluid temperature was 70.4^oC while the maximum water temperature at the bottom of the hot water tank was 59.9^oC. The annual average daily energy collected was 19.6 MJ/d, energy delivered by the solar coil was 16.2 MJ/d, supply pipe loss was 3.2 MJ/d, solar fraction was32.2%, collector efficiency was 45.6% and system efficiency was 37.8%.

A thermosyphon solar water heating system which captures and utilises the abundant solar energy to provide domestic hot water was designed, simulated, constructed and tested. The system was designed to supply a daily hot water capacity of 0.1m^3 at a minimum temperature of 70^oC for domestic use. From the research he concluded that a thermosyphon solar system with collector area of 2.24 m^2 operated under the weather condition of Zaria, would be capable of supplying a daily domestic water of 0.1m^3 at temperature ranging from 59^oC for the worst month (August) to 81^oC for the best month (April). He found values of 0.663, 0.956 and 0.885 and the low values of 8.09^oC, 3.65^oC and 5.31^oC between the modelled tank inlet temperature and the observed tank inlet temperature for the three days tests conducted indicated that the model formulated using transient system software was valid and closely agreed, capable of predicting the performance of the system with a 66.3 %, 95.6% and 88.5 % degree of accuracy for the 3 days that the experiments were conducted respectively (Selfa, 2015).

In an experiment conducted by (Kumar *et al.*, 2013) on evaluating the performance of solar water heating system, they carried out on 11.00am, 11.15am, 11.30am, 12.10pm and 12.40pm and found out inlet temperatures of 32.2^0C, 42.1^0C, 34.6^0C, 36.9^0C and 35.2^0C and outlet temperatures of 52.8^0C, 83^0C, 78.4^0C, 83.2^0C, and 60.9^0C respectively on flat plate collectors. The corresponding efficiencies were found to be 20.84%, 21.48%, 36.73%, 20.55% and 12.13%.

2.2 Solar water heating system components

Solar water heating systems can be divided into two categories: active and passive. Active systems use pumps to circulate a heat-transfer fluid through the collectors, while passive systems rely on gravity to circulate water through the system.

2.2.1 Passive systems

Passive SWH systems do not use a pump to circulate water from the solar collector to the water storage tank. In their most simple form, passive systems are usually water storage tanks located inside of an insulated box with a glazed surface as the fluid heats up its density decreases. The fluid becomes lighter and rises to the top of the collector where it is drawn to the storage tank. The fluid which has cooled down at the bottom of the storage tank then flows back to the collector. When the sun shines and is hot enough the water in the tank heats up and flows to the solar storage tank via gravity. Active systems though less expensive than passive solar water heaters are better suited for areas with hot weather, since frozen water can cause pipes to burst (Dilip *et al.*, 2012).

2.2.2 Active systems

There are generally two types of active solar water heating systems: direct circulation systems and indirect circulation systems.

Direct circulation systems utilise a portable water pump through the solar collectors and into the home's water heater. Because the system is pumping potable water into the collectors, they are most preferred in areas that do not have long periods of low temperatures or freezing and that do not have hard or acidic water.

For cold weather climates, indirect circulation systems are the much better suited because they pump a heat-transfer fluid through the collectors. The heated fluid is then pumped through a heat exchanger in an insulated water heater, where it transfers the heat from the fluid to the potable

SWH systems can be classified broadly into two categories depending on the nature of heat transfer through the working fluid: direct systems and indirect systems. In the direct system, water is heated directly in the collector. In the indirect system, a heat transfer fluid is heated in the collector which is then passed through a condenser or a heat exchanging device to heat water. Similarly, depending on the circulation of working fluids, SWH systems can also be grouped into either: passive circulation system or active circulation system. Passive circulation systems refer to thermosyphonic method in which the density difference induces the circulation of the fluid, naturally. On the other hand, active circulation employs a pump to effect forced circulation of the working fluid (Raisul *et al.*, 2012).

2.2.3 Thermosyphon systems (Passive)

This is a passive system that works on the principle of density difference to transport heat energy. Potable heat transfer fluid (i.e., water) is heated by a solar collector and the natural convection drives the water from the solar collector unit to the hot water storage tank unit. Water becomes less dense due to solar heating and expands according to the temperature rise. Hot water is circulated to the storage tank, and the relatively cooler water from the bottom of the tank is circulated to the solar collector device. This flow is dependent on the duration of sunshine, since it aids density variation which in turn affects the flow of water. To reduce pipe friction, a larger pipe diameter is recommended rather than the normal size (2–3 in. diameter). Usually, connecting lines are kept at an angle to prevent the development of larger air bubbles that would resist the flow of water. Also, the solar collector–inlet is connected to the bottom of the storage tank to avoid reverse flow. In situations, where the collector working pressure is less than the direct supply of city water, suitable pressure reduction valves are used. Usually an auxiliary heater is included to augment the heating process of a SWH, in particularly when used in solar adverse regions (Raisul *et al.*, 2012). Thermo-syphon systems account for almost 75% of installed capacity and are mainly used in warm climates, such as in Southern China, Africa, South America, Southern Europe and the Middle East and Africa (MENA) region. They are less suitable for cooler climates because of the high heat loss from external hot water stores and the danger of freezing during winter time (IRENA, 2015).

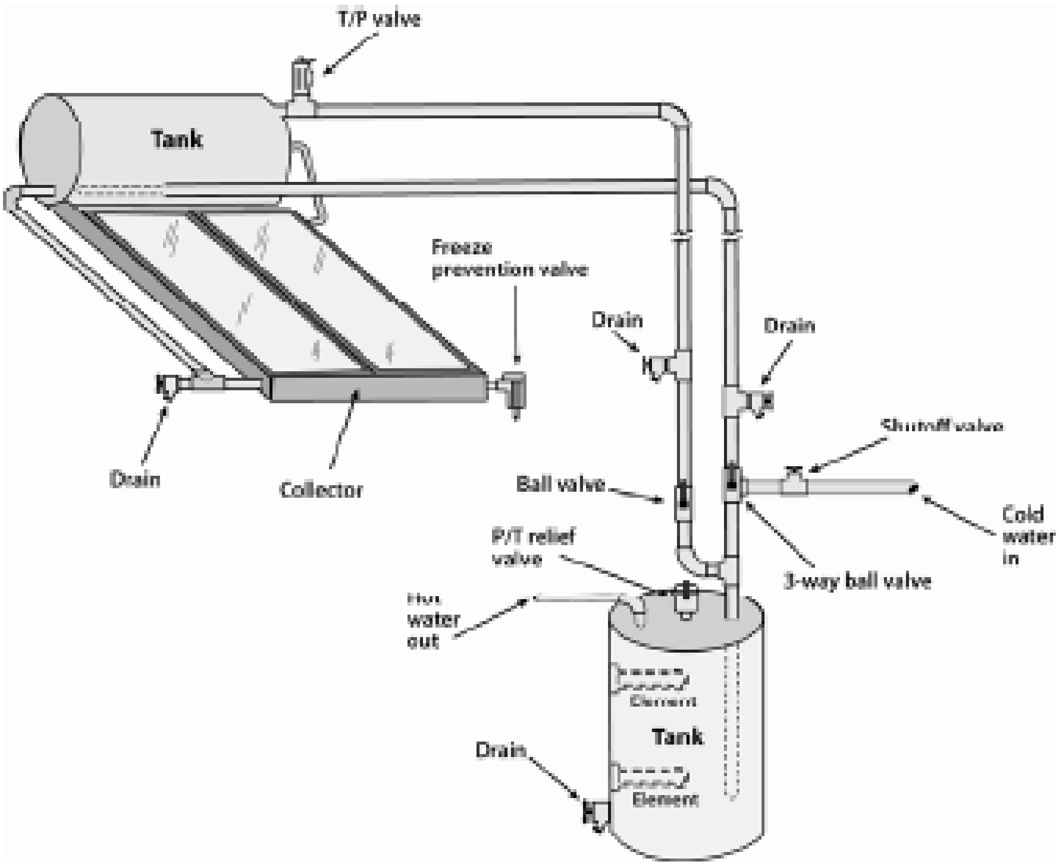

Figure 2.2- Thermosyphon system(passive)(Source: Solar domestic hot water heating systems, Christopher,2009.)

2.2.4 Integrated collector storage (ICS) systems (passive)

Unlike the conventional SWH system in which a collector acts as an absorber of sunlight, the ICS system utilizes both the collector as well as the storage tank as an absorber to collect solar radiation. In most cases, the entire exterior part of the reservoir acts as an absorber. However, these systems are subjected to heavy heat losses, especially during non-sunshine hours. Several measures, such as selective absorber surface coatings, insulating materials, and a single or double glazing glass covers have been used to reduce the heat losses. A few other techniques were also attempted to culminate the heat loses: movable protection cover, insulated baffle plate, and utilizing phase change material (PCM) inside the storage tank. Researchers have also attempted to use transparent insulating materials for the appropriate exposed parts. Further, to reduce the heat losses, the storage tank was operated on thermal stratification modes, by drawing the hot water from the top of the storage tank and cold water inlet to the bottom of the tank.

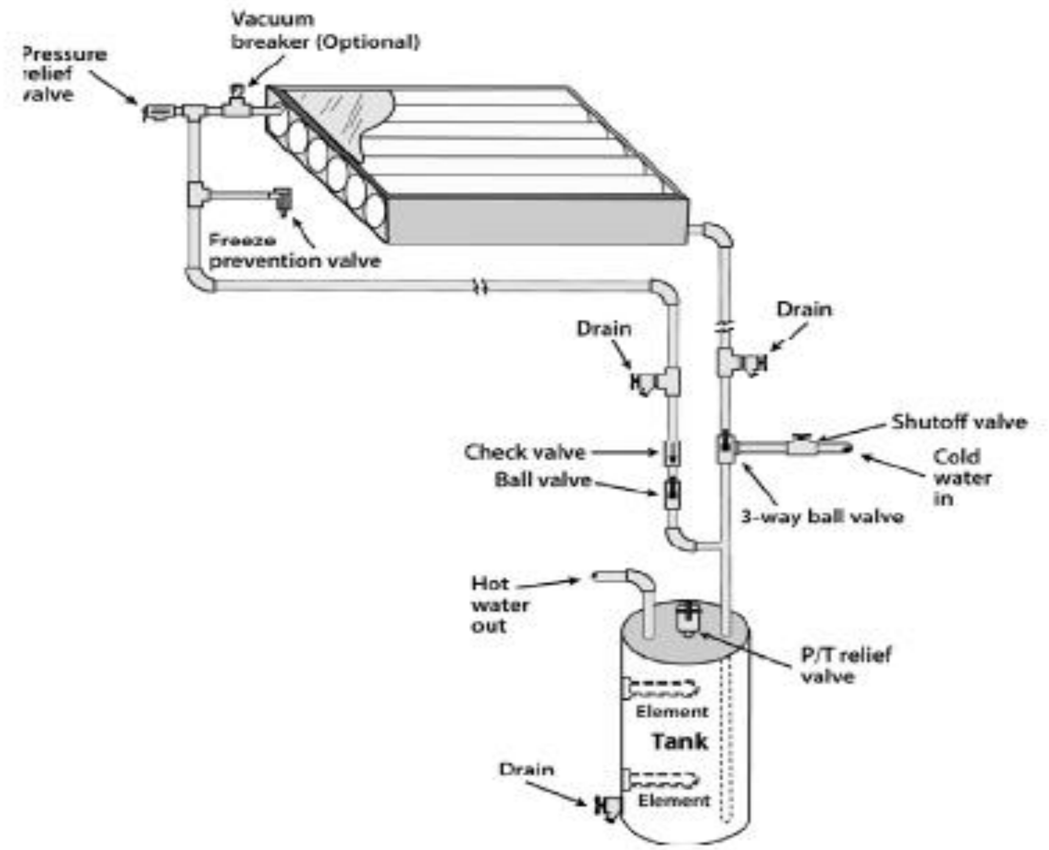

Figure 2.3- Intergrated collector system(Passive)(Source: Florida solar energy centre, 2006)

2.2.5 Batch system

The simplest of all solar water heating systems is a batch system. It is simply one or several storage tanks coated with a black, solar-absorbing material in an enclosure with glazing across the top and insulation around the other sides. It is the simplest solar system to make and is quite popular with do-it-yourselfers. When exposed to direct sun during the day, the tank transfers the heat it absorbs to the water it holds. The heated water can be drawn for service directly from the tank or it can replace hot water that is drawn from an interior tank inside the residence.

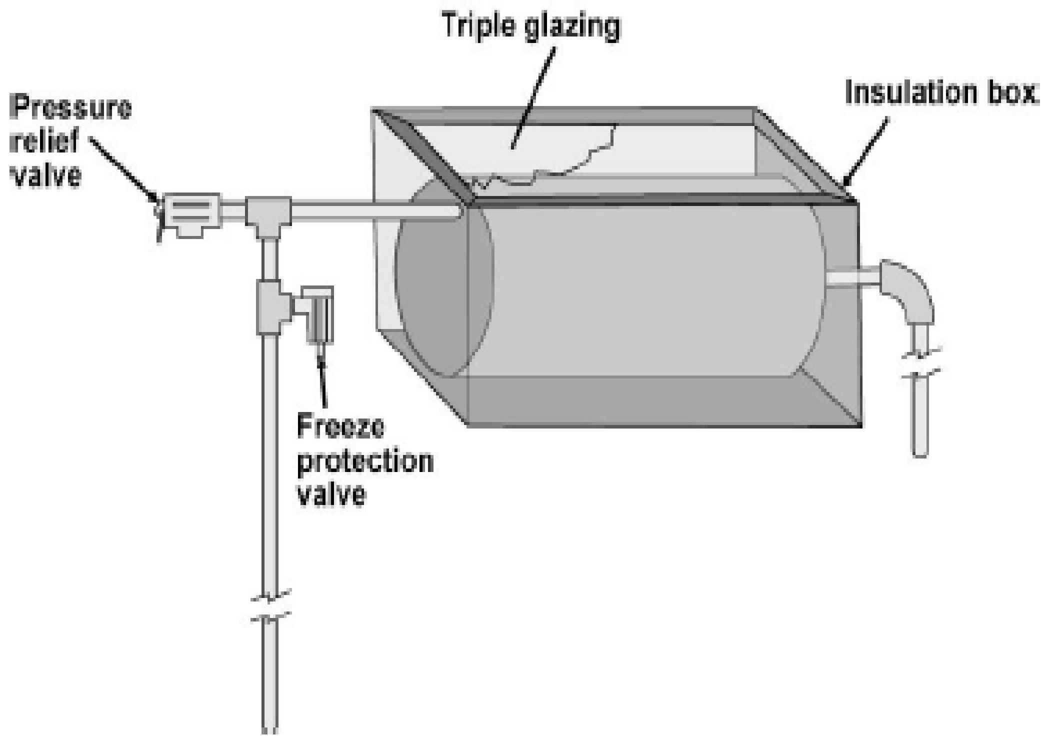

Figure 2.4- Batch system (Source: Solar domestic hot water heating syatems, Christopher,2009.)

2.2.6 Direct circulation systems (active)

Unlike thermosyphon systems, direct circulation systems require a pump to circulate water from storage tank to the collector to get heated. The hot water flows back to the storage system and is ready for the end-user. The pump is usually controlled by a differential thermostat that regulates water at the top header by a sufficient margin to the bottom of the tank. A check valve prevents the reverse circulation to avoid night time thermal losses from the collector. The collectors can be positioned either above or below the storage tank as pump is used to activate circulation. Direct circulation system is generally used only under situations when freezing is not a concern. Sometimes, water from the cold storage tank or city water supply can be used directly into the system. Care should be taken when quality of water is hard or acidic, in a direct circulation system since it would result in scale deposition which in turn may cause clogging or corrosion of the collector tubes. Direct circulation systems more commonly employ a single storage tank which is with an auxiliary heater. However, in few case-studies, two-tank storage systems have been used as well.

Active direct systems are principally differentiated by their pump control or freeze protection scheme. They can either be differential controlled, photovoltaic controlled or timer controlled.

2.2.7 Differential controlled

In a differential controlled system, the circulating pump operates when sensors located at the top of the collector (hottest point) and bottom of the storage tank (coldest point) indicate a 5-20^{o} F temperature difference. Thereby, the water always gains heat from the collector when the pump operates. When the temperature difference drops to about 3-5^{o}F, the pump switches off. During the course of the day, the controller is constantly comparing the two sensor temperatures. In this way, water circulates through the collector only when sufficient solar energy is available to increase the water temperature (Florida solar energy centre, 2006).

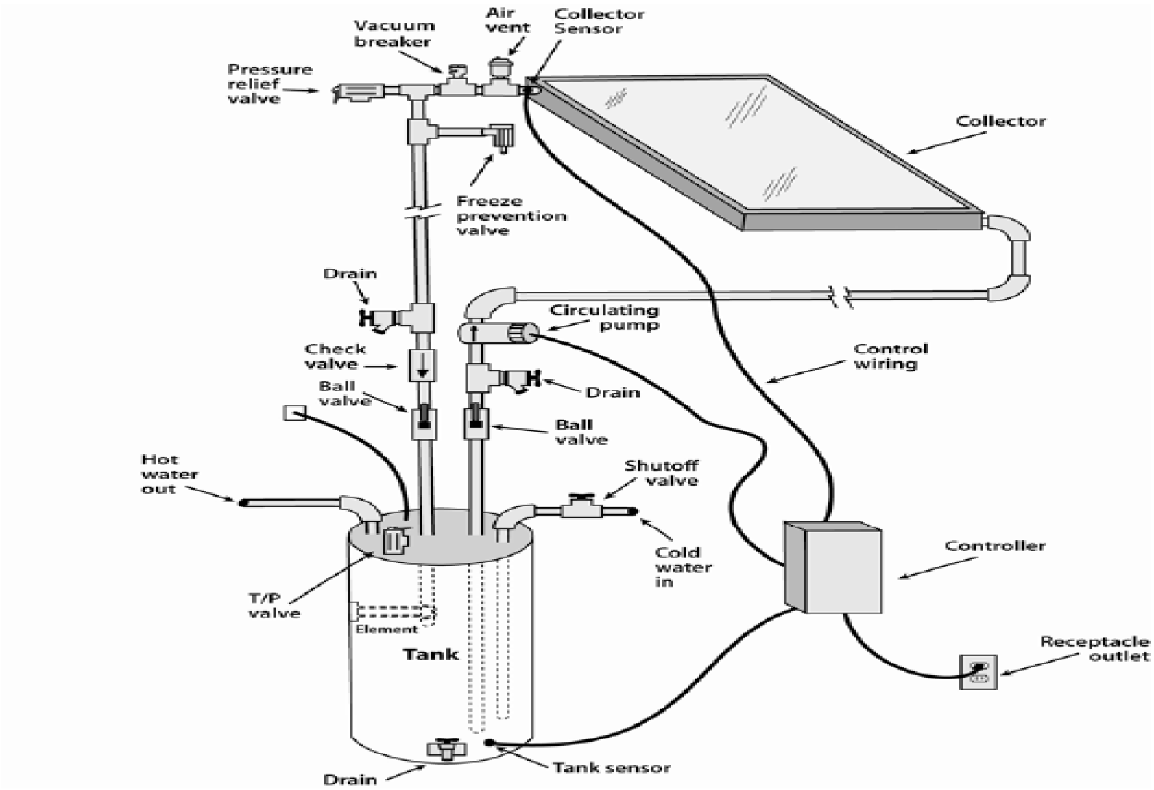

Figure 2.5- Diffrential controlled active direct system (Source: Florida solar energy centre, 2006)

2.2.8 Photovoltaic controlled

The photovoltaic (PV) controlled system uses a PV module to perform these functions. Photovoltaics modules are semiconductor materials that convert sunlight directly to direct current (DC) electricity. In a photovoltaic controlled-system, a photovoltaic module generates power for a DC pump that circulates water through the collector and back into the storage tank. In a direct-coupled system, the module and pump are sized and properly matched to ensure that the pump is operating when sufficient solar energy for heating water is available and will stop operating when solar energy diminishes.

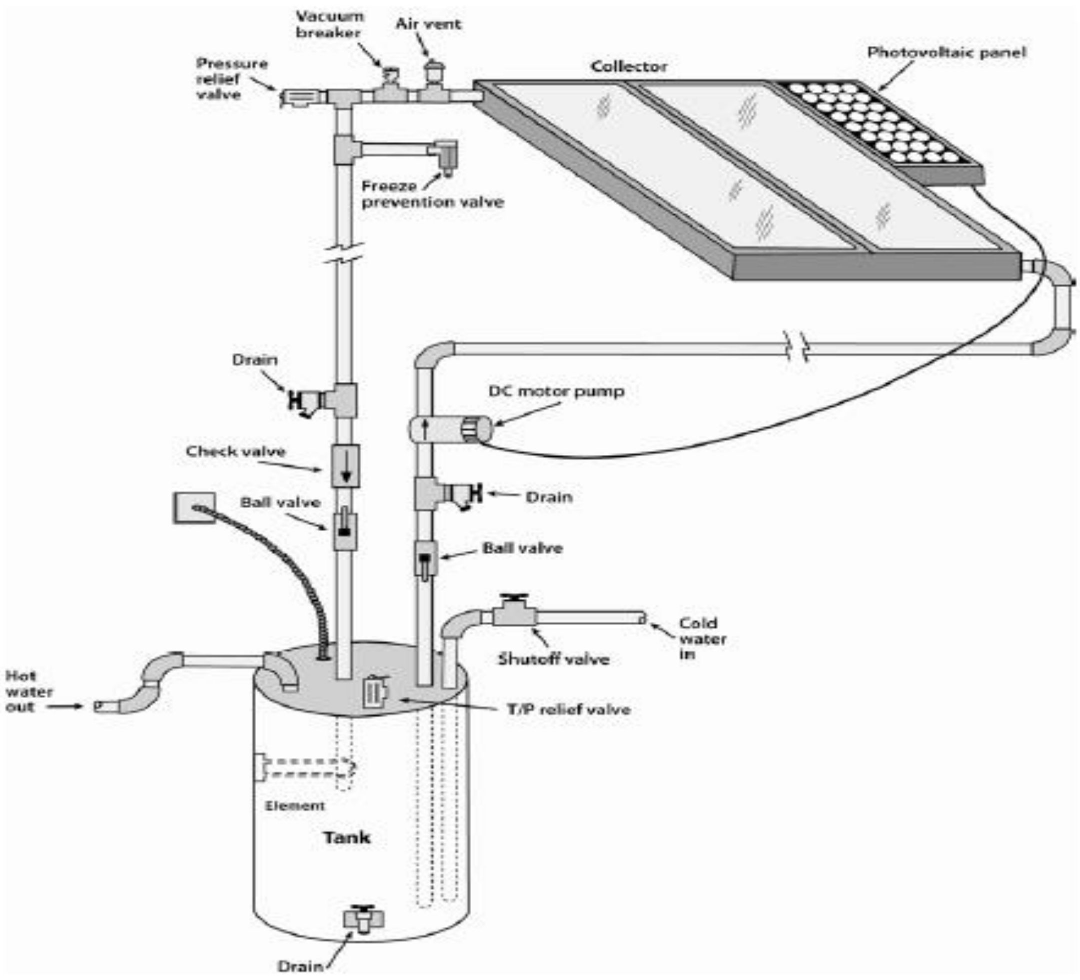

Figure 2.6- Photovoltaic controlled active direct system (Source: Florida solar energy centre, 2006)

2.2.9 Timer controlled

This control method is used in tropical climates where temperatures are mild year-round and significant amounts of solar energy are available almost every day. In a timer controlled system, a timer turns on a pump in mid-morning and switches it off in late afternoon. To ensure that the heated water stratifies at the top of the storage tank, the system uses a very small pump. The collector feed and return lines are both connected through the use of a special valve at the bottom of the storage tank so only the coldest water from the tank flows through the solar collector.

Timer controlled systems could conceivably operate during rain or overcast conditions, so care must be taken to ensure the supply and return lines to the collector are located near the bottom of the storage tank. Therefore, if the pump operates during a cloudy day, only a small amount of the water at the very bottom of the tank was circulated through the collector. This prevents potential major tank heat loss.

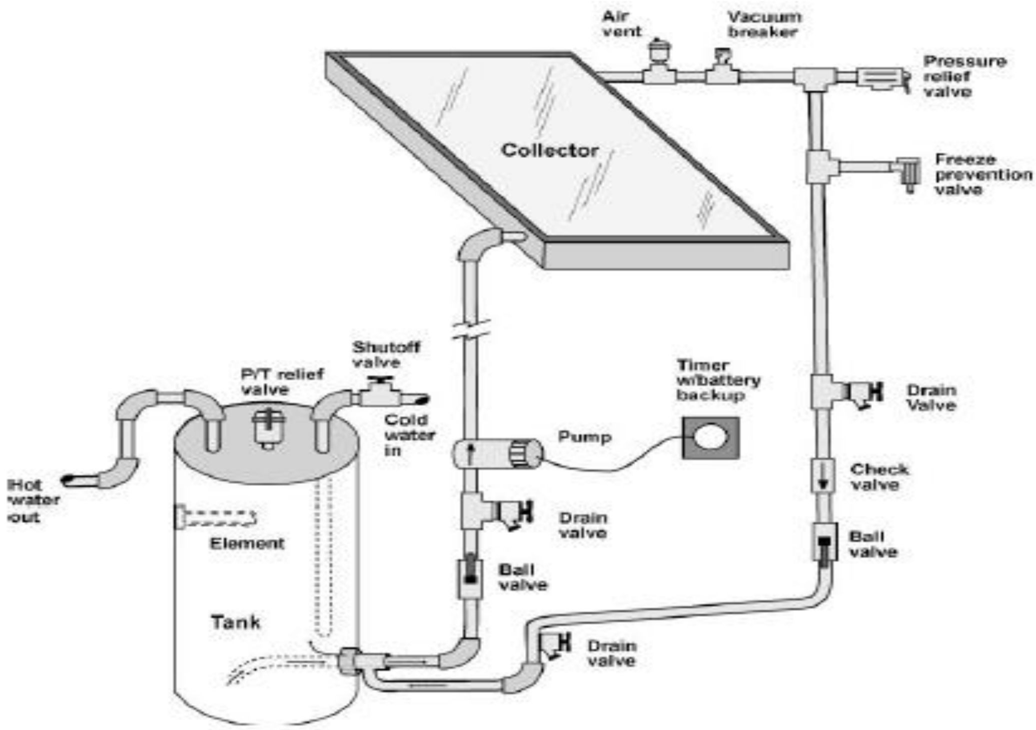

Figure 2.7- Timer controlled active direct system (Source: Florida solar energy centre, 2006)

2.2.10 Indirect water heating systems (active)

Indirect systems are typically used in areas of freezing temperatures or areas that have water that is very high in mineral content. The combination of high dissolved minerals and high temperatures produced by the solar system can accelerate scale build-up in system piping, fittings, and valves.

Indirect systems of SWH utilize two circulation loops to effect heating: (a) the closed-collector loop and (b) the open storage tank loop. Usually, the heat transfer fluid is circulated within the closed-collector loop, to gain the heat and is then passed through a heat exchanger where heat is transported to the potable water that flows in an open loop to the storage tank. There are several different types of working fluids used in the closed loop, such as water, refrigerants, and anti-freeze mixtures. The heat exchanger can either be an internal system (placed inside the water storage tank or outside of the storage tank) or as an external system. An expansion tank integrated with a pressure relief valve is used in the closed circulation loop system. In the pressurized system, the tank is provided (an additional expansion tank) to have a control on temperature and pressure of the working fluid. However, for the unpressurized system, the tank is provided to release the pressure when required to vent.

2.2.11 Air systems (active)

Unlike water or other refrigerants, air has also been used as working fluid, for its unique advantages. Compared to the convectional SWH system, air can be used as a working fluid even during freezing weather conditions, is non-corrosive and requires only low maintenance requirements. However, the system is generally large and requires large space of air handling unit. Fans and dampers are incorporated to aid the system operation. The heat gained by the air in the collector duct is released through a heat exchanger to aid domestic hot water supply of up to 80^0C.

2.3 Solar water heater components

SWH consist of a solar radiation collector panel, a storage tank, a pump, a heat exchanger, piping units and auxiliary heating unit. Active systems need controls for pump operation and valves for safety and proper operation. Passive systems utilize many of the same components but in some cases for different reasons.

Solar collectors capture the sun's electromagnetic energy and convert it to heat energy. While most direct and indirect active systems use flat-plate collectors, some systems employ evacuated tube collectors, or use collectors that incorporate one or more storage tanks.

The collector is made up of cover glass, which reduces upward thermal losses. It also has an absorber plate which absorbs as much of the irradiation as possible while losing little heat as possible upward to the atmosphere and downward through the casing back. This absorber plates then transfer heat retained to the transport fluid. The absorptance of the surface collector depends on the colour and nature of the coating material and angle of incidence (Owura, 2012)

The storage tank holds the water that has been heated by the collector. The water can be stored in any vessel suitable for high temperatures. The tanks can be pressure rated depending on the application and whether or not a back-up heating system is used. Most solar water heating tanks are made of stainless steel, copper, or mild steel with a heat resistant protective coating inside for avoidance of corrosion. To reduce heat losses, the tanks are insulated with rock wool insulation pads or polyurethane foam. The insulation is covered with aluminium sheet cladding, reinforced fibre glass; fibre glass reinforced plastic (FPR) or suitable grade plastic cover.

An active system uses a pump or circulator to move the heat transfer fluid from the storage tank to the collector. In pressurized systems, the system is full of fluid and a circulator is used to move hot water or heat transfer fluid from the collector to the tank. Pumps are sized to overcome static and head pressure requirements in order to meet specific system design and performance flow rates.

Piping provides the path for fluid transport in the system. The piping must be compatible with system temperatures, pressures and other components. Most systems use copper piping because of its durability, resistance to corrosion and ability to withstand very high temperatures. Galvanized iron pipes and fittings are normally used for plumbing in solar water heating. Piping for solar water heating should be well insulated to minimise thermal losses. The insulation should be further protected by suitable aluminium or high density polyethylene (HDPE) pipe cladding.

In active solar water-heating systems, the controller acts as the "brains" of the system. When the controller determines that sufficient solar energy is available at the collector, it activates the pump to circulate water to the collector and back to the storage tank. The most frequently used types of controllers include differential, photovoltaic and timer

Indirect systems have heat exchangers that transfer the energy collected in the heat-transfer fluid from the solar collector to the potable water. Heat exchangers can be either internal or external to the storage tank. Common heat exchanger designs are the tube-in-tube, shell-in-tube, coil-in-tank, wraparound-tube, wraparound-plate and side-arm designs.

2.4 Solar collectors

In a solar collector, a special energy exchanger converts solar irradiation energy either to the thermal energy of the working fluid in solar thermal applications, or to the electric energy directly in PV (Photovoltaic) applications. For solar thermal applications, solar irradiation is absorbed by a solar collector as heat which is then transferred to its working fluid (air, water or oil). The heat carried by the working fluid can be used to either provide domestic hot water/heating, or to charge a thermal energy storage tank from which the heat can be drawn for later use (at night or cloudy days) (Tian *et al.*, 2012).

There are two main types of collectors used in SWH and these are: -

2.4.1 Flat plat collectors

Flat plate collectors are designed to heat water to medium temperatures and are usually permanently fixed in position, and therefore need to be oriented appropriately.

This type of collectors consists of tubes carrying a fluid running through an insulated, weather-proof box with a dark absorber material and thermal insulation material on the backside that also prevents heat loss. The simplest collector is an unglazed collector without backside insulation, typically used for heating swimming pools and other low-temperature applications, while glazed FPC have higher efficiencies, lower heat loss, high working temperatures and higher initial cost.

This is an extension of the basic idea to place a collector in an 'oven'-like box with glass in the direction of the Sun. Most flat plate collectors have two horizontal pipes at the top and bottom, called headers, and many smaller vertical pipes connecting them, called risers. The risers are welded (or similarly connected) to thin absorber fins. Heat-transfer fluid (water or water/antifreeze mix) is pumped from the hot water storage tank (direct system) or heat exchanger (indirect system) into the collectors' bottom header, and it travels up the risers, collecting heat from the absorber fins, and then exits the collector out of the top header. Serpentine flat plate collectors differ slightly from this "harp" design, and instead use a single pipe that travels up and down the collector. However, since they cannot be properly drained of water, serpentine flat plate collectors cannot be used in drain back systems (Soteris, 2004).

The type of glass used in flat plate collectors is almost always low-iron, tempered glass. Being tempered, the glass can withstand significant hail without breaking, which is one of the reasons that flat-plate collectors are considered the most durable collector type.

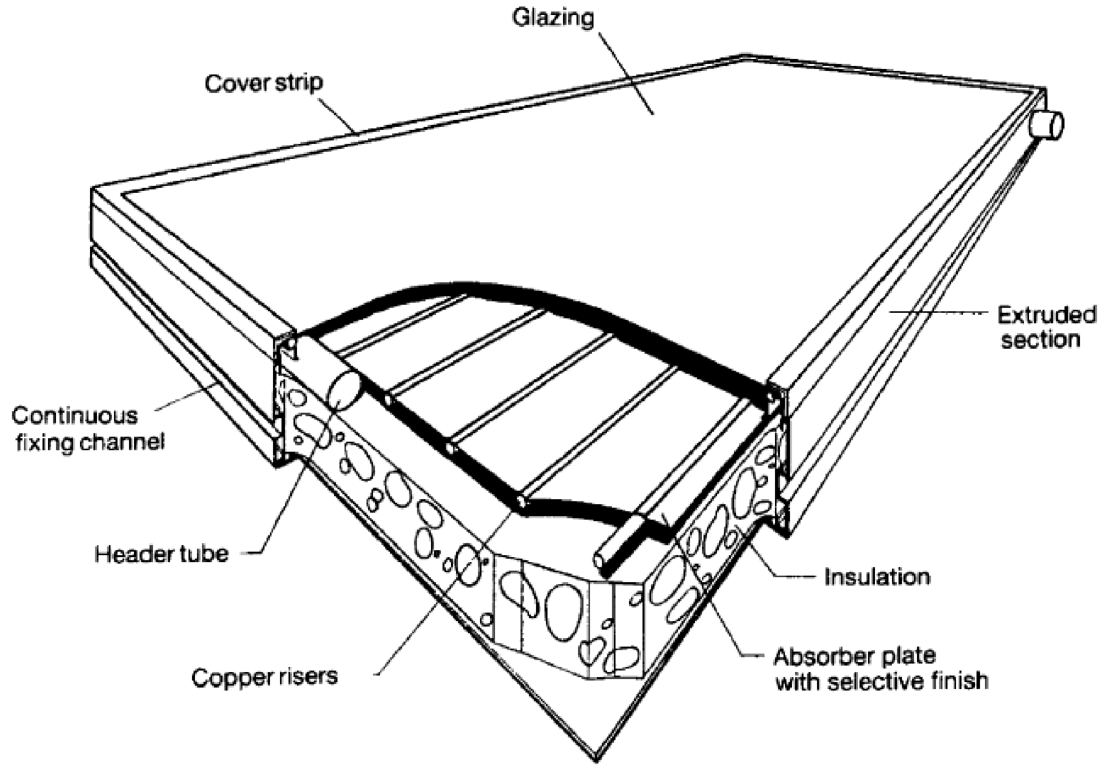

Figure 2.8- Flat plate collector (Source: Florida solar energy centre, 2006)

2.4.2 Evacuated tube collectors

Evacuated-tube collectors generally have a smaller solar collecting surface because this surface must be encased by an evacuated glass tube. They are designed to deliver higher temperatures.

This type of collectors uses parallel rows of glass tubes, each of which contains either a heat pipe or another type of absorber, surrounded by a vacuum. This greatly reduces heat loss, particularly in cold climates. The absorber can be made from metal or glass, the latter also known as a “double-wall” or “Sydney style” tube. Apricus ETC have both a double-wall glass tube and as well as a heat pipe. The production and use of ETC is increasing due to increased automation of the production process

Evacuated tube collectors are a way in which heat loss to the environment, inherent in flat plates, has been reduced. Since heat loss due to convection cannot cross a vacuum, it forms an efficient isolation mechanism to keep heat inside the collector pipes. Since two flat sheets of glass are normally not strong enough to withstand a vacuum, the vacuum is rather created between two concentric tubes. Typically, the water piping in an ETC is therefore surrounded by two concentric tubes of glass with a vacuum in between that admits heat from the sun (to heat the pipe) but which limits heat loss back to the environment. The inner tube is coated with a thermal absorbent. Life of the vacuum varies from collector to collector, anywhere from 5 years to 15 years.

Flat plate collectors are generally more efficient than ETC in full sunshine conditions. However, the energy output of flat plate collectors is reduced slightly more than evacuated tube collectors in cloudy or extremely cold conditions. Most ETCs are made out of annealed glass, which is susceptible to hail, breaking in roughly golf ball -sized hail. ETCs made from "coke glass," which has a green tint, are stronger and less likely to lose their vacuum, but efficiency is slightly reduced due to reduced transparency

2.4.3 Integral collectors

In integral collector storage (ICS) and batch solar water-heating systems, the collector functions as both solar absorber and water storage.

Unlike the conventional SWH system in which a collector acts as an absorber of sunlight, the ICS system utilizes both the collector as well as the storage tank as an absorber to collect solar radiation. In most cases, the entire exterior part of the reservoir acts as an absorber. However, these systems are subjected to heavy heat losses, especially during non-sunshine hours. Several measures, such as selective absorber surface coatings, insulating materials, and a single or double glazing glass covers have been used to reduce the heat losses. A few other techniques were also attempted to culminate the heat loses: movable protection cover, insulated baffle plate, and utilizing phase change material (PCM) inside the storage tank. Researchers have also attempted to use transparent insulating materials for the appropriate exposed parts. Further, to reduce the heat losses, the storage tank was operated on thermal stratification modes, by drawing the hot water from the top of the storage tank and cold water inlet to the bottom of the tank (Raisul *et al.*, 2012)

ICS collectors generally incorporate 4" or larger diameter horizontal metal tanks connected in series by piping from a water inlet at the bottom of the tank to an outlet at the top. The tanks, which are coated with either a selective or moderately selective absorber finish, are enclosed in a highly insulated box covered with multiple glazing layers. The multiple glazing layers and selective coatings are designed to reduce the heat loss of water stored in the absorber (Florida solar energy centre, 2006)

2.4.4 Unglazed or formed collectors

These are similar to flat-plate collectors, except they are not thermally insulated nor physically protected by a glass panel. Consequently, these types of collectors are much less efficient for domestic water heating. Unglazed collectors, as depicted in are usually made of a black polymer. They do not normally have a selective coating and do not include a frame and insulation at the back; they are usually simply laid on a roof or on a wooden support. These low-cost collectors are good at capturing the energy from the sun, but thermal losses to the environment increase rapidly with water temperature particularly in windy locations. As a result, unglazed collectors are commonly used for applications requiring energy delivery at low temperatures (pool heating, make-up water in fish farms, process heating applications, etc.) For pool heating applications, however, the water being heated is often colder than the ambient roof temperature, at which point the lack of thermal insulation allows additional heat to be drawn from the surrounding environment. (Natural resources Canada, 2001).

2.5 Factors that affect the performance of solar water heaters

The Size of the Storage Tank should be chosen according to the collector area and the daily heating load requirements. Bigger tanks tend to keep hot water for longer durations due to thermal inertia. This then means the bigger the tank is the more advantageous it was during cloudy days and incoming cold water will have a lower overall effect when you draw off hot water (Florida solar energy Centre, 2006).Commercial tanks are roughly sized by using the formula of 50 litres per day capacity for each person in a household plus another 50 litres for general household use but for a daily system you can safely and cost effectively double that estimation.

Surface area is the most important factor in designing solar water heating system. The larger the surface area means more pipes was exposed to the sun thus more water heated. Collector area is usually dependent on the storage tank capacity. Usually the standard requirement for moderate climates are with a tank of 5.6 litres requires a collector of $0.09m^2$ per square foot. While for hot climates a tank of 7.5 litres requires a collector of $0.09m^2$ per square foot is used in f-chart solar water heating system design procedure (Duffie and Beckmann, 2013)

In order to achieve maximum collector performance, the orientation is critical. Usually homestead solar water heater collectors in the Southern hemisphere should face due north and in the Northern hemisphere, due south. Depending on the location and collector tilt, the collector can face up to 90° east or west of true south without significantly decreasing its performance. The Optimum tilt angle for solar collector is an angle equal to the latitude (Owura, 2012)

Insulation on Tanks and Piping is important because the less standby heat lost the longer the water will stay warm and the less the homemade solar water heater system has to work to heat it up again. It also helps to extend the time hot water was available under cloudy conditions.

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

Hot Water Demand to be used in a given time plays a major role in determining a systems performance. That is the more the hot water needed at a given time the worse your system will perform due to overload of larger volume of incoming cold water which has to be heated up to the required temperature. The hot water demand in Kenya can be calculated using the Table below.

Table 2.1- Hot water demand calculation table (source: ERC, 2006)

Type of building	Specific Daily Hot water Demand (DHWD) in litres per day at 60^0C
Domestic residential houses	30 per person
Educational institutions such as colleges and boarding schools	5 per student
Health institutions such as hospitals, health centres, clinics and similar medical facilities	50 per bed
Hotels, hostels, lodges and similar premises providing boarding services	40 per bed
Restaurants, cafeterias and similar eating places	5 per meal
Laundries	5 per kilo of clothes

Geographic Location in that the closer you get to the equator, the more energy the sun will provide to heat water, due to the fact that the surface of the earth faces the sun directly there.

As you travel north or south the curvature of the earth means that the same amount of the sun's rays covers a larger surface area and therefore the energy supplied diminishes.

Kenya's geographical location means it has different temperature zoning with average annual temperatures between 10^0C and 30^0C. Temperatures are affected by elevation and relief, at coastal areas and around Lake Victoria Sea and land breeze must be taken into account as they affect temperature. Highlands have low temperature while lowlands have highest temperatures (Obiero and Onyando, 2013)

Kenya is divided into seven different climatic zones; this zoning will have influence the performance of the solar water heating collector. Different zones have different sunshine hours with lowlands having more hours than the highlands. Below is a table showing climatic zones.

Collector Array Arrangement and there are basically two arrangements of connecting collectors which are parallel and series connections. In parallel connection, module inlet and outlet ports are fed to the common respective headers. The performance of the collector array is thus the same as the performance of the individual collector. In series connection, the performance of the second and subsequent modules will not be the same as the first because its inlet temperature is the outlet temperature of the first (Duffie and Beckmann, 2013).

CHAPTER THREE

Materials and Methods

This section covers research design that was used in the study, locale of the study, materials that were used, data collection techniques and methods of evaluating the performance of existing solar water heaters

3.1 Study Design

Descriptive survey method was used in evaluating the performance of solar water heaters and the study design was non-experimental and involved using the existing solar water heaters installed at different apartments and hotels.

3.2 Study area

The study was conducted in Nairobi county formerly Nairobi Province which is subdivided into 17 parliamentary constituencies and is located between longitudes at 36^{0}39' and 37^{0}06'East and latitudes 1^{0}09' and 1^{0}27'South. Its altitude is 1795m above the sea level and adjacent to the eastern edge of the Rift Valley.

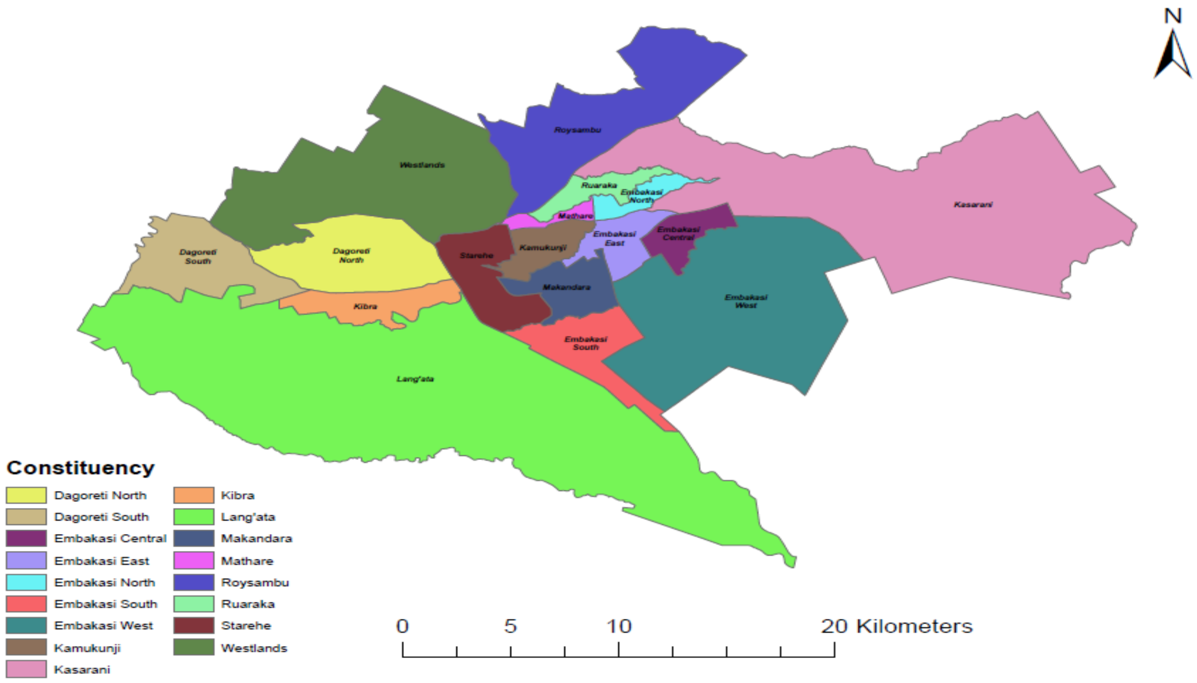

Figure 3.1 site map (IEBC, 2011)

3.3 Sampling Method

In this case Purposive sampling (Critical case sampling) was used. According to Mugenda and Mugenda (2003) 10% to 30% of the total population is appropriate for the study. The respondents were selected from premises which have installed solar water heating systems using random sampling technique involving cluster sampling method. It was conducted in all the constituencies each being accorded equal chance of participation.

Sample Size Determination for the residents was done using the Fisher formula as recommended by Mugenda & Mugenda (1999) .When the population is more than 10,000 individuals, 384 of them are recommended as the desired sample. With the total installed working systems being 77,000 systems and with Nairobi County having 40% of the total installed systems then the accessible population in this area of study was 30,800 systems thus the formula below was used

$$n_f = \frac{n}{1 + \frac{n}{N}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where;

n_f = Desired sample size when population is less than 10,000

n = Desired sample when the population is more than 10,000

N = Estimate of the population size

Using the above formula then sample size will be:

$$n_f = \frac{384}{1 + \frac{384}{30{,}800}}$$

=379 systems

3.4 Sample size

Proportional random samples of the premises and households were selected from each sub-county.

Table 3.1 shows sample households within the entire county

Sub-County	**Number of Households**	**Sample Households**	**Random Sample(30% random sample)**
Westlands	9,000	130	39
Starehe	650	13	4
Ruaraka	2,350	24	7
Roysambu	1,800	20	6
Mathare	100	5	2
Makadara	600	11	3
Langata	4,200	32	10
Kibra	650	13	4
Kasarani	1,200	15	5
Kamukunji	150	5	2
Embakasi West	150	5	2
Embakasi South	200	6	2
Embakasi North	250	7	2
Embakasi East	1,500	17	5
Embakasi Central	1,000	14	4
Dagoretti South	2,500	27	8
Dagoretti North	4,500	35	11
Total	**30820**	**379**	**116**

During research the following methods were used: -

Monitoring was done on outlet water temperatures from the collector and this involved taking readings on the temperature display unit between 09.00am to 16.00pm with intervals of 1hr each. Most installed solar water heaters have an outlet temperature display unit that is provided during installation.

Temperature measurement- Measurement of inlet water temperature was measured using an infrared thermometer and this entailed pointing the infrared rays on the inlet pipe while varying the location of the rays. The temperatures were measured between 09.00am and 16.00pm with intervals of 1hr each and recorded on a table.

Since the collectors installed on the field are of different sizes, then the change in collector area has an effect thus it was necessary to measure different sizes. To determine the effect of collector area on the outlet temperature one collector was covered halfway with an opaque material and the change in temperature observed.

The data was then recorded in the table as shown below.

Table 3.2 - Showing the recording for time against temperature for Evacuated tube collectors

	Apartment Outlet Temp in °C				
Time of the day	**Apart A**	**Apart B**	**Apart C**	**Apart D**	**Apart E**
09.00 am	35.3	35	79.5	47	43.8
10.00 am	32.7	40	80	50	48
11.00 am	30.4	45	81.3	57	45
12.00	39	60	84	62	60
01.00 pm	45	67	85.9	69.4	65
02.00 pm	68	75	90	75	78
03.00 pm	65	73	85	70	75
04.00 pm	64	60	74.6	65	60

Angle measurement- Solar hot water collectors should be oriented geographically to maximize the amount of daily and seasonal solar energy that they receive. Some of the factors to consider are roof orientation (if the collector is mounted on the roof), local landscape features that shade the collector daily or seasonally, and local weather conditions (foggy mornings or cloudy afternoons), as these factors may affect the collector's optimal orientation. Nowadays, most solar water heating collectors are mounted flat on the roof. This is more aesthetically pleasing than rack-mounted collectors, which stick up from the roof at odd angles. Thus, most collectors have the same tilt as the roof.

Although the optimal tilt angle for the collector is an angle equal to the latitude, fixing the collector flat on an angled roof will not result in a big decrease in system performance. But the roof angle must be taken into account when sizing the system.

The angles were measured using digital inclinometer that is usually used in construction industry. This was done by placing the inclinometer which has an arm length of 60cm on the roof top and adjusting one arm of the tool which is capable of measuring 0-270^0 with an accuracy of ± 0.1^0 and since it is lying on the roof then the arm is adjusted until the point where the other arm touches the roof and then the readings shown were recorded.

Insolation measurement - Solar insolation was measured using the Hukseflux thermal sensors application software installed on iphone. The iphone is placed in the same angle as the solar collector and then the software refreshed in order to give the insolation at that given hour.

Since the evaluation was done in Nairobi and the study locale is big, then an assumption was used that the insolation of Nairobi region has a small margin of error and therefore measurement was carried out at one location in a premise at Industrial area.

Thermal performance determination - In order to determine the thermal performance, the following were collected: the storage tanks capacity, the inlet and outlet temperatures of the fluid and the specific capacity and density of the fluid. Different SWH systems have different thermal performance, Inlet temperatures were collected using infrared thermometers and this simply uses infrared light which is directed to the inlet pipe and it records the temperature. Outlet temperatures were recorded from the temperature display unit.
The following equation (i) was used to determine the thermal performance.

$$Q_{out}=mC_p(T_{o-}T_i)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where

Q_{out} is the heat energy output, m is mass flow rate of the fluid, C_p is the coefficient of performance and $T_o$is the outlet temperature and $T_i$is the inlet temperature.

The mass flow rate was used by measuring the volumetric flow rate of water over a given duration of time and then from the volume then the mass flow was calculated as follows

Mass flow rate = Volume flow rate x density…………………………. (3)

After the determination of thermal performance, the data was recorded in a table as shown below.

Cost benefit Analysis - This is important in decision making on whether the solar water heaters are profitable and of help to the user. Carrying out this analysis will help in determining the payback period and financial analysis of the project undertaken. The concept of life cycle cost evaluation of solar water heater is important as it gives an overview of what has been undertaken. The initial cost of solar water heater system is recovered through savings of energy bills over a period of time. Life cycle cost (LCC) is the sum of all the costs associated with an energy delivery system over its lifetime, and takes into account the time value of money. The life cycle savings (LCS), for a solar plus auxiliary system, is defined as the difference between the LCC of a conventional fuel-only system and the LCC of the solar plus auxiliary system. This is equivalent to the net present value (NPV) of the gains from the solar system compared to the fuel-only system (Soteris, 2004).

Therefore, the analysis will be carried out using provided calculations and T-SOL software to determine the financial analysis. The net present value (NPV) of a time series of cash flows for both incoming and outgoing is defined as the sum of the present values (PVs) of the individual cash flows of the same entity. It compares the present value of money today to the present value of money in future, taking inflation and returns into account

Collector efficiency - In order to determine the collector efficiency, the following equation was used (Beckmann and Duffie, 2013)

$$\eta_c = {mC_p(T_o - T_i)}\Big/{A_c\,G_t} \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where A_c is collector area and G_t is total Global solar radiation.

Tools and Test gears

No.	Component	Specification
1	Hukseflux Pyranometer	Standard for solar irradiation
2	DC/AC Multimeter	10^3-100Amps
3	Tape measure	50m
4	Infra-Red Thermometer	For measuring inlet temperature
5	Angle inclinometer	Standard for Construction

3.5 Data Processing and Analysis

Inlet and outlet temperatures, solar insolation, collector size, storage tank capacity, orientation angle and electricity consumption were collected through measurement and observation of validated standard measuring instruments relevant to the variables involved in the study. The data collected was processed using Excel, to generate the means, coefficient of correlation and coefficient of regression with the help of equations i, ii and iii. Presentation of data collected was done but not limited to tables and graphs which include line graphs, bar graphs and histograms.

The effect of collector size, collector orientation, storage tank capacity and inlet and outlet temperatures was analysed and conclusion for the performance of solar water heaters made based on the research findings.

In this study T-SOL software was used to analyse the data found and this was used to determine the cost benefit analysis of solar water heating system to determine on the savings attained by using the SWH. T-SOL is a dynamic software programme used to simulate and optimise solar thermal systems such as hot water systems and space heating applications. This is preferred to other analysis tools because it has an integrated MeteoSyn tool which allows users to create climate data for locations outside of the included data base. It also requires a few input parameters such as project climate data location, system consumption, collector type selection and system configuration selection to automatically size the collector and storage tank. It provides project report, economic efficiency calculation and annual simulation of the system as output (Valentin, 2017). In this thesis, the T-SOL method of simulating and analysing the performance of the solar water heating is based on two distinct collectors; one with a flat plate collector and the other with an evacuated tube collector. Also T-SOL was applied in order to simulate the operation of the solar water heating system annual performance and enable the identification of the system in a year.

Financial analysis was also analysed with the help of T-SOL and from the software it was easy to get the internal rate of return and also a graph was generated showing the operation years, profit and initial investment of the system

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results from monitoring of the installed flat plate solar water heaters

In this research temperatures of Premises installed with SWH were monitored and this was done in intervals of one hour between 9.00 am and 4.00 pm and the table below shows readings of inlet and outlet temperatures and respective flow rates of the SWH.

Flat plate collectors are an extension of the idea to place a collector in an 'oven'-like box with glass directly facing the Sun. Most flat plate collectors have two horizontal pipes at the top and bottom, called headers, and many smaller vertical pipes connecting them, called risers. The risers are welded (or similarly connected) to thin absorber fins. Heat-transfer fluid (water or water/antifreeze mix) is pumped from the hot water storage tank or heat exchanger into the collectors' bottom header and it travels up the risers, collecting heat from the absorber fins, and then exits the collector out of the top header.

Table 4.1- Average Collector area against temperature for flat plate collectors (8th to 24th May, 2017)

Time of the day	Outlet Temperature (^{0}C) for Collector Area 2.9 m^2	Outlet Temperature (^{0}C) for Collector Area 3.6 m^2	Outlet Temperature (^{0}C) for Collector Area 4 m^2	Outlet Temperature (^{0}C) for Collector Area 4.6 m^2
9.00 am	26.5	30	40	42
10.00 am	34	42	48	53
11.00 am	36.3	46	54	60
12.00	38	48	56	60
01.00 pm	40	57	60	65
02.00 pm	50	62	64	67
03.00 pm	48	55	60	59
04.00 pm	42	49	53	50

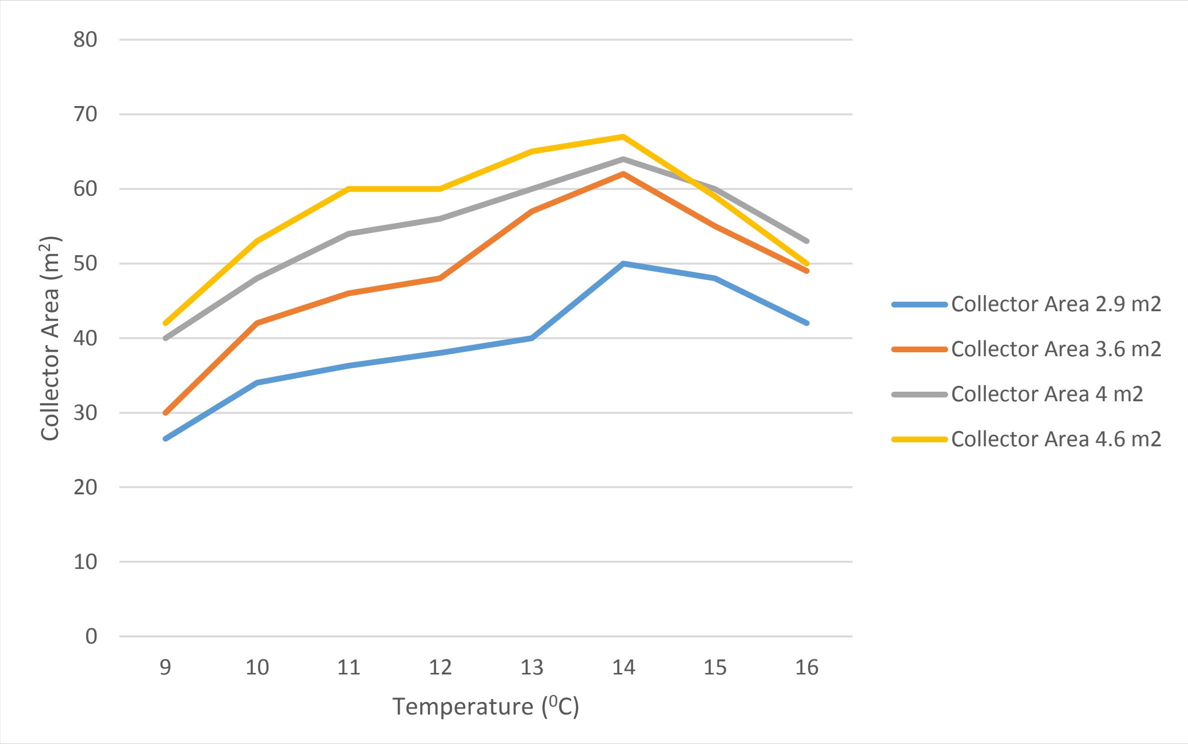

Figure 4.1- Graph of temperature against collector area for flat plat collectors

The figure 4.1 above illustrates the temperatures of different flat plate collector sizes from 2.9m^2,3.6m^2,4m^2 and 4.6m^2. From the graph it is seen that the small the collector the less the temperature at each given time and as sunshine increases its insolation, then the temperature subsequently increases and the highest temperature is recorded at solar noon when the sun is overhead. According to literature, more solar insolation is experienced between 12.00 and 02.00 pm and this are the durations when the temperatures are highest with a high of 50, 62, 64 and 67^{0}C respectively according to collector size.

There is also a sudden rise in temperature from 9.00 am to 11.00 am and this can be attributed to the fact that flat plate collectors have a high sunlight picking or absorption and due to that then the temperature rises rapidly until 12.00 when it starts having a slight increase. From the graph the temperature is dependent on the collector area and the bigger the area, the more the temperature and vice versa.

4.1 Results from monitoring of the installed evacuated tube solar water heaters

The Evacuated tube collector consists of a number of rows of parallel transparent glass tubes connected to a header pipe and which are used in place of the blackened heat absorbing plate in the flat plate collector. These glass tubes are cylindrical in shape. Therefore, the angle of the sunlight is always perpendicular to the heat absorbing tubes which enables these collectors to perform well even when sunlight is low such as when it is early in the morning or late in the afternoon, or when shaded by clouds.

Evacuated tube collectors are made up of a single or multiple rows of parallel, transparent glass tubes supported on a frame. Each individual tube varies in diameter from between 25mm to 75mm and between 1500mm to 2400mm in length depending upon the manufacturer. The tubes are made of borosilicate or soda lime glass, which is strong, resistant to high temperatures and has a high transmittance for solar irradiation.

Table 4.2 –Average Collector area against temperature for evacuated tube collectors (12th to 28th June, 2017)

Time of the day	Outlet Temperature (^{0}C) for Collector Area 2.9 m^2	Outlet Temperature (^{0}C) for Collector Area 3.6 m^2	Outlet Temperature (^{0}C) for Collector Area 4 m^2	Outlet Temperature (^{0}C) for Collector Area 4.6 m^2	Outlet Temperature (^{0}C) for Collector Area 6.9 m^2
9.00 am	30.4	35	43.8	47	79.5
10.00 am	32.7	40	45	50	80
11.00 am	35.3	45	48	57	81.3
12.00	39	60	60	62	84
01.00 pm	45	67	65	69.4	85.9
02.00 pm	68	75	78	75	90
03.00 pm	65	73	75	70	85
04.00 pm	64	60	60	65	74.6

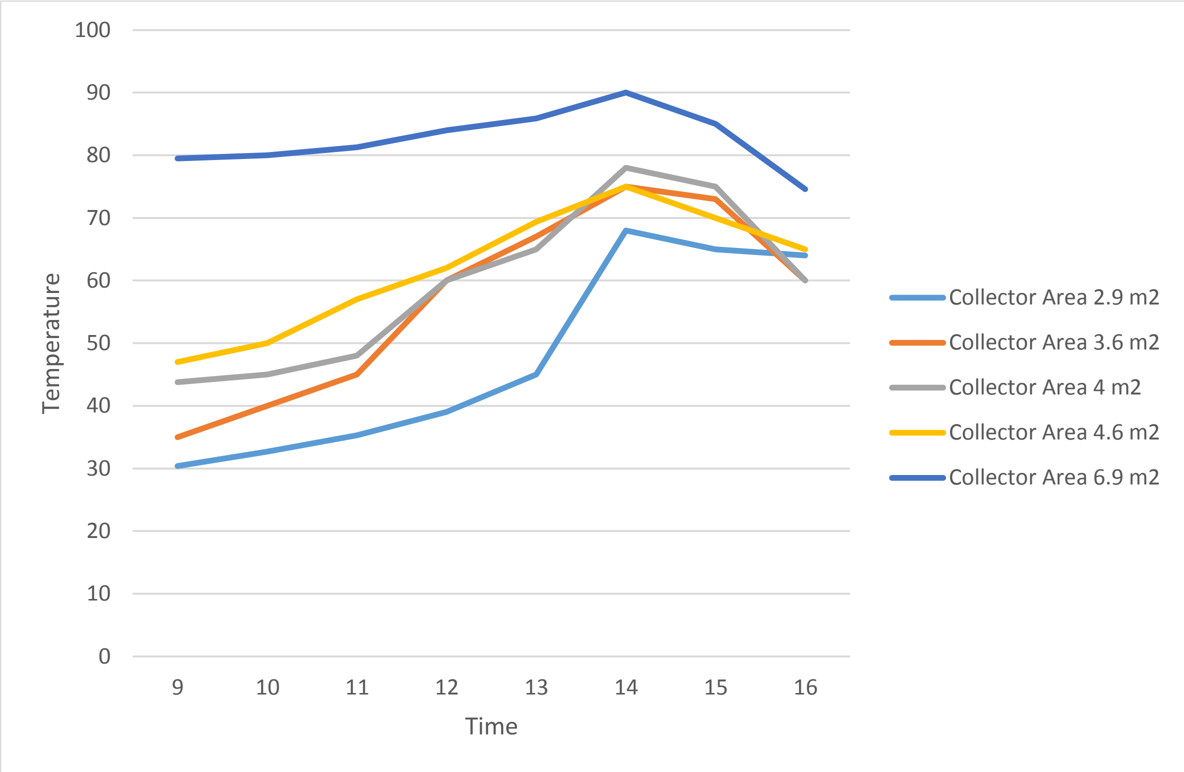

Figure 4.2-Graph of temperature against collector area for Evacuated Tube Collectors.

Figure 4.2 above shows results obtained by monitoring outlet temperatures of different vacuum tubes collector sizes of $2.9m^2$, $3.6m^2$, $4m^2$, $4.6m^2$ and $6.9m^2$ at different times of the day. From the graph it is evident that collector area matters a lot when it comes to temperature and it is shown that $6.9m^2$ collector panels has the highest temperature of water recorded at 90^0C at 02.00 pm. The collector having the smallest area among the ones monitored is $2.9m^2$ which has a temperature of 68^0C at 02.00 pm. Comparing all the collector sizes at the same time then it gives an indication that collector area matters a lot in collecting enough sunlight and thus giving a difference in temperatures.

In order to determine further the effect of collector area on the temperature, two different collectors with the same area were covered with different opaque material for a duration of 30 minutes and the area covered was altered and it was found that the smaller the area the less the temperature and vice versa.

From figure 4.2, it is evident that temperature increase is dependent on time of the day. As time advances then the insolation increases and subsequently increases in temperature with highest values recorded at 02.00 pm in all the collector sizes and then the temperature starts dropping from 03.00 pm up to 04.00 pm. Also it is evident that as collector size increases it results subsequently to increase in temperature from the smallest to the largest and this is due to larger exposure area to the sun which results to increased heating of the fluid.

From comparison of the two solar water heaters, the flat plate solar collector has the largest heat absorbing area, but it also has the highest heat loss. The primary advantage of the flat plate solar collector is that it is able to collect both direct and diffuse solar irradiation; this feature makes it collect more heat in the mornings and lose heat fast whenever the sun rays reduces. It is inexpensive to manufacture and can be integrated as a part of the roof construction, which makes it even more economically feasible.

Evacuated solar collectors are an alternative to flat plate solar collectors. Due to the vacuum enclosing the absorbing surface, convective heat loss is eliminated and the performance of the solar collector is higher than for flat plate solar collectors.

ETC's have a round shape and therefore able to collect sunlight at all times of the day and thus makes them have high fluid temperatures than FPC's. It is this ability that makes them the most preferred nowadays and they can produce very hot water under best angles.

Results from tilt angle and corresponding Temperatures per Apartment for FPC's

Table 4.3- Average Tilt angle and corresponding temperatures for Flat plate collectors (8th to 24th May, 2017)

Time of the day	Outlet Temperature (°C) at tilt angle 32	Outlet Temperature (°C) at tilt angle 35	Outlet Temperature (°C) at tilt angle 40	Outlet Temperature (°C) at tilt angle 45
9.00 am	26.5	30	40	42
10.00 am	34	42	48	53
11.00 am	36.3	46	54	60
12.00	38	48	56	60
01.00 pm	40	57	60	65
02.00 pm	50	62	64	67
03.00 pm	48	55	60	59
04.00 pm	42	49	53	50

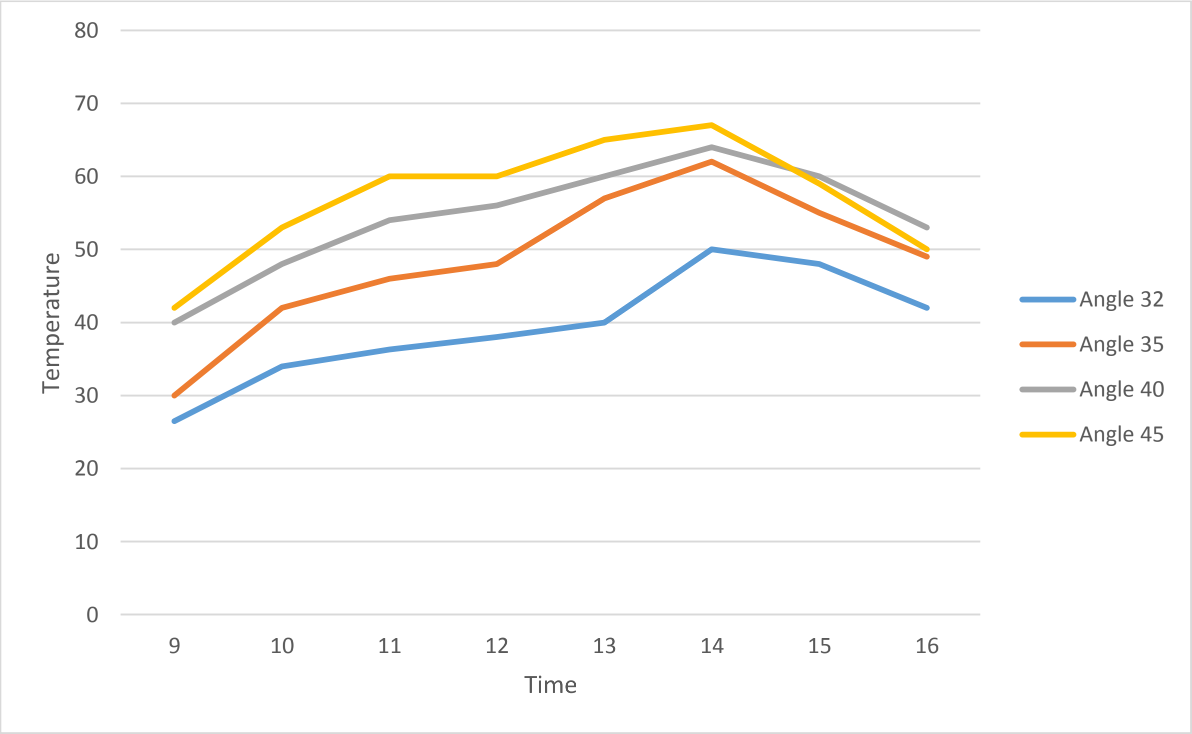

Figure 4.3- Graph of Temperature against tilt angle for flat plate collectors

The figure 4.3 above illustrates the effect of varying the tilt angle of flat plate solar collectors at different times of the day and the installed collector's angles were 32^0,35^0,40^0 and 45^0. In this case at 32^0 it was found that the highest temperature recorded was 50^0C and this value was realized at 02.00 pm while the lowest temperature at this orientation was 26.5^0C at 9.00 hours. The highest temperature was at 45^0 and at this angle the highest recorded temperatures was 67^0C and at this angle the lowest temperature value was 42^0C at 9.00 am.

The performance of Flat plate collectors largely depends on the orientation and the most suitable angle in this case is 45^oC which has the highest recorded temperature as compared to the other angles and this angle does not have much variation from the optimum angle of installation in Nairobi.

Flat plate collectors absorb maximum solar energy only at solar noon. This factor is known as 'incidence angle modification' and should be adjusted for in estimating solar energy systems.

They are typically designed with an unsealed enclosure. This can make them prone to condensation over time, thus reducing their overall temperatures. Flat plate collectors are more susceptible to ambient heat loss because the fluid being heated has considerable residence time in the flat plate collector as it travels through the collector. The fluid in an evacuated tube system only flows through the header manifold minimizing residence time and also flat plate collectors generally have 1" of insulation on the sides and bottom.

From research conducted by (Sivakumar *et al.*, 2012) he found out that the maximum outlet temperatures were recorded at 01.00 pm and the outlet temperature reduced after 01.00 pm until 05.00 pm which is almost as the results obtained in this research which shows that the temperature reduces from 03.00 pm upto 04.00 pm.

Results for tilt angle and corresponding Temperatures per apartment for ETC's

Table 4.4 – Average Tilt angle and corresponding temperatures for evacuated tube collectors (12th to 28th June, 2017)

Time of the day	Outlet Temperature (⁰C) at tilt Angle 30	Outlet Temperature (⁰C) at tilt Angle 32	Outlet Temperature (⁰C) at tilt Angle 35	Outlet Temperature (⁰C) at tilt Angle 40	Outlet Temperature (⁰C) at tilt Angle 45
9.00 am	30.4	35	43.8	79.5	47
10.00 am	32.7	40	45	80	50
11.00 am	35.3	45	48	81.3	57
12.00	39	60	60	84	62
01.00 pm	45	67	65	85.9	69.4
02.00 pm	68	75	78	90	75
03.00 pm	65	73	75	85	70
04.00 pm	64	60	60	74.6	65

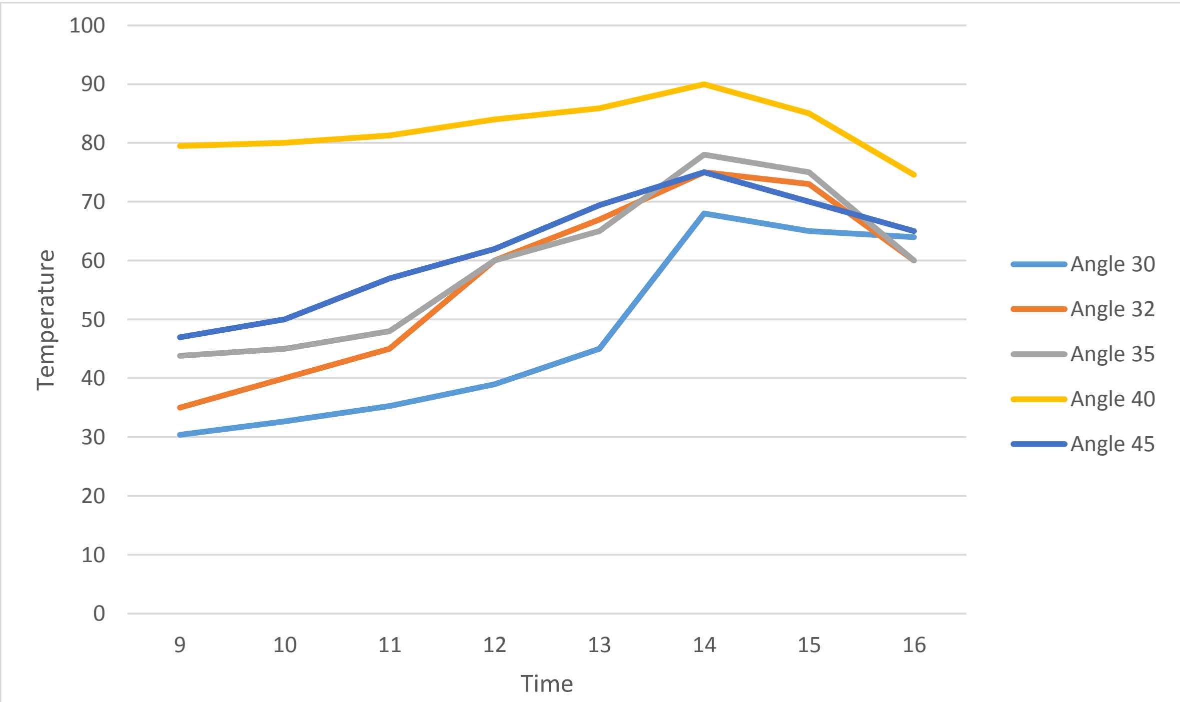

Figure 4.4 -Graph of temperature against the tilt angle for Evacuated Tube Collectors

The figure 4.4 above illustrates the effect of varying the tilt angle of solar collectors at different times of the day and the installed collector's angles were 30,32,35,40 and 45^0. From the above it was found that the less the angle the less the temperature recorded and the more the tilt the more the temperature but this tilt is only limited to 45^0 which after exceeding this angle the temperature starts decreasing. In this case at 30^0 it was found that the highest temperature recorded was 68^0C and this value was realized at 02.00 pm while the lowest temperature at this orientation was 30.4^0C at 11.00 am. The highest temperature was at 40^0 and at this angle the highest recorded temperatures was 90^0C and at this angle the lowest temperature value was 74.6^0C at 04.00 pm. From this research, exceeding the optimum angle shows that there is a drop in temperature.

From this graph there is a variation in temperature ranges at different angles since at different angles and time, the sun differs and hence the difference.

From literature the peak solar radiation occurs at solar noon, when the sun is highest in the sky. The low angle of the sun at sunrise and sunset means that the atmosphere filters the sunlight more and results in less energy being delivered to the earth's surface. Therefore, from the research conducted then at 02.00 pm is the time when radiation is at peak and thus high outlet temperature of water. This agrees to experiments conducted by (Arekete, 2013) in which he found that highest temperatures were attained during this time.

4.2 Monthly solar radiation

Solar radiation was measured for a duration of one month as shown in the table and then an average of the whole month was done.

Table 4.5 – Measured values of solar insolation for May and June 2017-Industrial Area

Day	Monthly Recorded Solar energy in $kWh/m^2/day$ May	June
1	6.5	6.1
2	6.32	5.8
3	6.1	5.72
4	6.44	5.85
5	6.2	5.9
6	6	4.8
7	6.22	4.8
8	6.1	4.6
9	5.7	5.9
10	5.4	5.4
11	5.2	4.6
12	4.7	3.78
13	4.2	3.8
14	3.9	4.1
15	3.76	5.7
16	3.8	5.4
17	4	4.32
18	4.1	4.75
19	4.4	4.9
20	4.5	5.8
21	6.3	5.4
22	6.4	4.7
23	6.2	5.38
24	5.3	4.8
25	5.8	5.3
26	4.75	5.8
27	3.8	5.7
28	4.7	5.4
29	5.3	5.35
30	5.8	5.8
31	6.1	

The irradiation was measured after duration of one hour between 9.00 am to 04.00 pm**.** The average solar insolation was for the month of May when the research was conducted and the insolation value was $5.4kW/m^2/day$. During this month the highest recorded insolation was between 01.00 pm and 02.00 pm since at this time the sun is hot compared to between 9.00 am to 12.00 pm and between 03.00 pm to 04.00 pm.

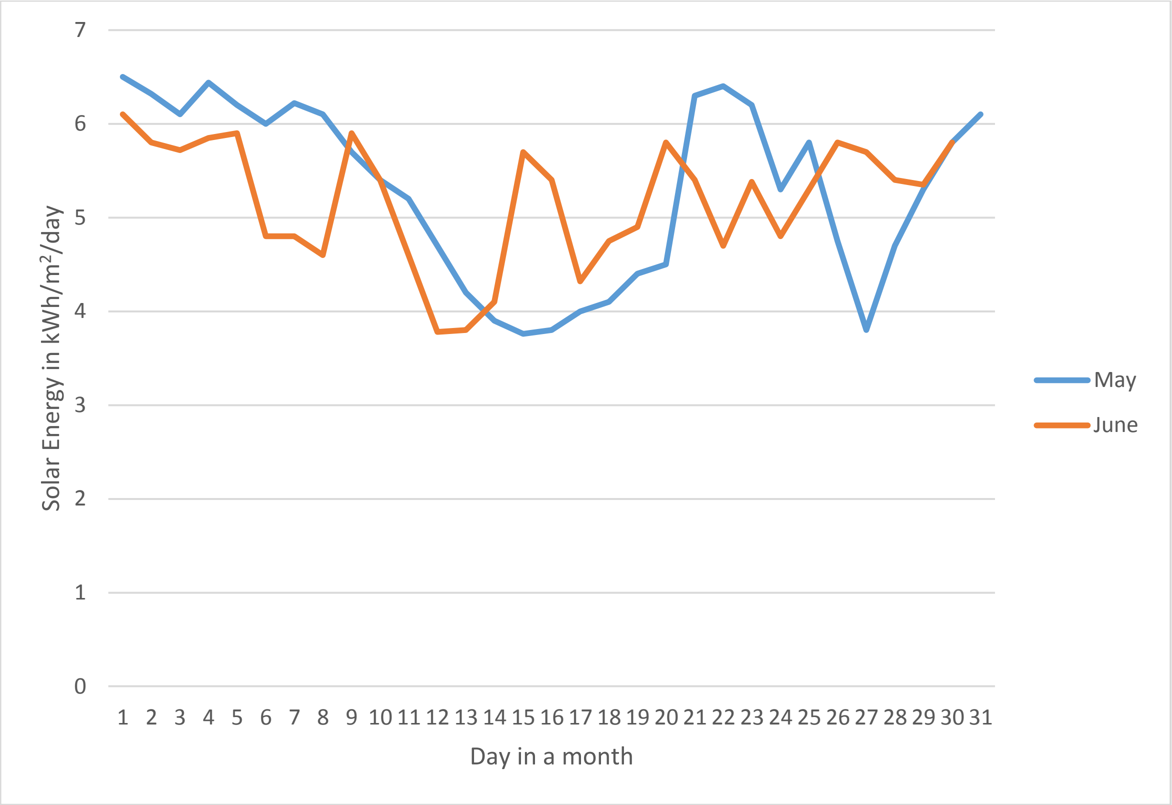

Figure 4.5- Recorded Solar energy in kWh/m^2/day

The highest measured value of solar energy was 6.5kWh/m^2/day while the lowest being 3.76 kWh/m^2/day. In May, Nairobi experiences more sunlight at the beginning of the month which makes it have a high solar insolation as compared to mid-month. As it enters June the insolation decreases since it is nearing July which experiences cloudier Month and most of the days in July are gloomy and chilly and with less solar energy. This research was conducted in May and part of June and that is the reason for recording the two months as shown in table 4.4 above. It was necessary to compare the results with the one measured at the meteorological department and this was to ensure that there is no major variation between the two figures and to reduce erroneous data from being recorded. The values obtained do not have much variation with that from Kenya meteorological station as shown in the table below.

Table 4.6 - Data obtained from meteorological station for the year 2017

	Solar energy Received in kWh/m2/day		
Month	**Mean**	**Max**	**Min**
Jan	6.68	8	4.87
Feb	6.87	7.93	5.46
Mar	6.71	7.96	5.05
Apr	5.52	6.79	3.79
May	4.88	3.6	3.76
Jun	4.43	5.35	3.78
Jul	4.18	5.52	3.03
Aug	4.37	5.43	3.25
Sep	5.72	6.46	4.76
Oct	5.86	6.47	4.72
Nov	5.46	6.53	4.48
Dec	6.04	7.49	5.07

From the table January has the highest solar insolation with a maximum of 8kWh/m^2/day with June having the lowest value of 5.35kWh/m^2/day. February recorded the highest minimum value of 5.46kWh/m^2/day while July recording the least minimum value of 3.03kWh/m^2/day. This value agrees with national average highlighted in the National Energy Policy, Sessional Paper No. 4 of 2004 on energy and also specified by (Newham, 1983) in which he found 5.5 kWh/m2/day as the national average and therefore his value is within the range found in this study. Kenya's average annual daily insolation is 6.0 kWh/m^2/day according to (Karakezi *et al.*, 2008). Solar and Wind Energy Resource Assessment (SWERA) report (Theuri, 2008), shows that the average annual daily insolation in the study area ranges from 4.5 – 4.75 kWh/m^2/day which falls within the range arrived at in this analysis.

4.3 Annual Thermal performance analysis of the system

This was done using the T-Sol software and this software is able to simulate the performance of DSWH using the parameters inputted such as desired temperature, average daily consumption, cold water temperature, total gross surface area and active solar surface area, tilt angle and number of collectors. In this case only one collector was considered in order to give an overview of how it will operate annually as shown below.

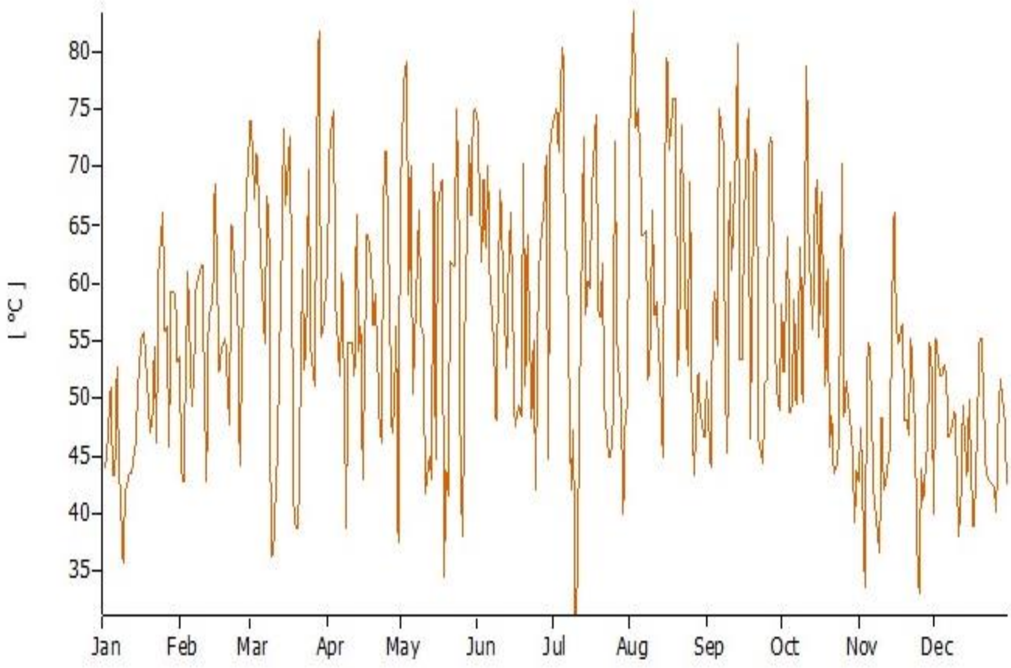

Figure 4.6 - T-SOL simulated annual maximum temperature for solar water heaters

The above calculations were carried out by T-Sol 2017 the simulation program for solar thermal heating systems. The results are determined by a mathematical model calculation with variable time steps of up to 6 minutes. Actual yields can deviate from these values due to fluctuations in climate, consumption and other factors. The system schematic diagram above does not represent and cannot replace a full technical drawing of the solar system.

In terms of the annual collector performance analysis, the FPC increases its value of solar fraction. FPC (Flat plate collector) has a higher percentage 56% compared to

ETC (Evacuated tube collector) 46%. CO_2emissions avoided are more in FPC as compared to ETC while efficiency of ETC is greater than that of FPC as shown in figure 4.7.

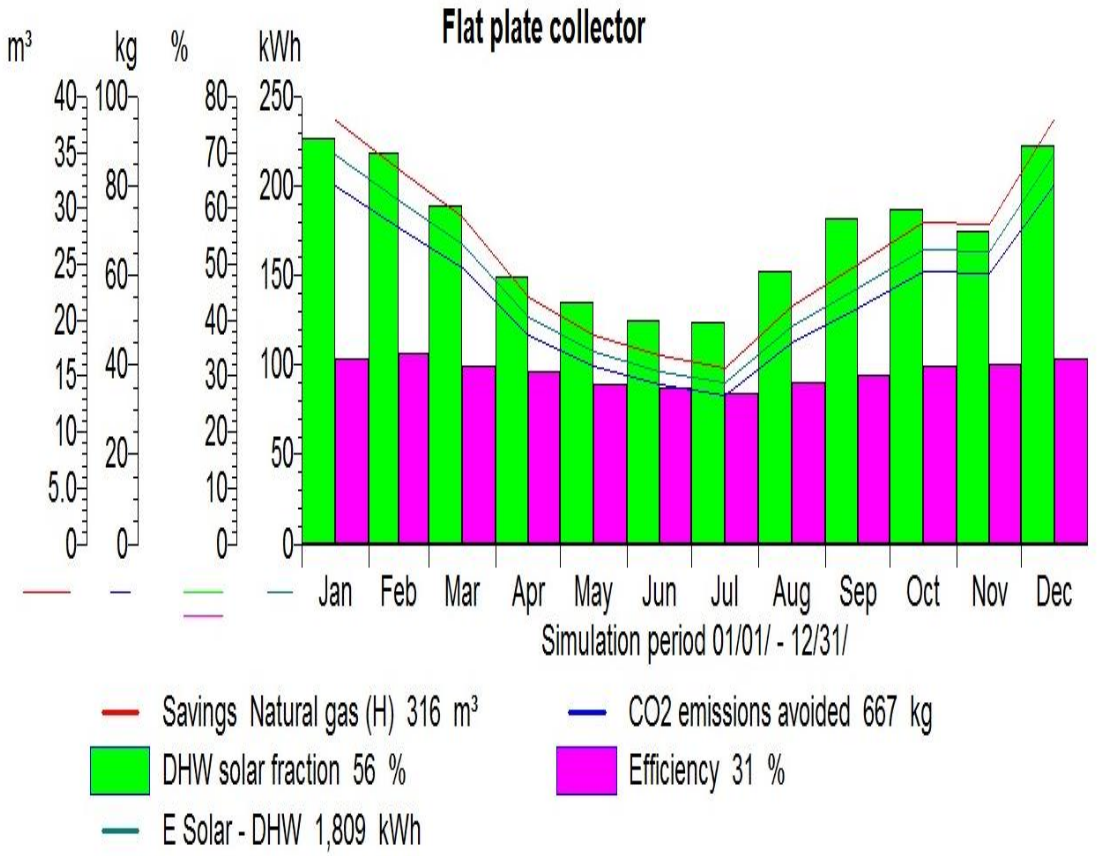

Figure 4.7 - Annual performance of Flat plat collector for Jan to Dec 2017

FPC effectiveness on simulating the thermal performance on T-SOL software as shown in figure 4.7 shows that the highest temperatures were attained in January, February, November and December 2017 and its highest efficiency was 21.6% for a collector area of 4.6$m^2$and the lowest efficiency was 19.13% for a collector area of 2.9m^2. This can be because FPC have a high picking of solar energy thus during this dry season, then more solar energy is available for heating.

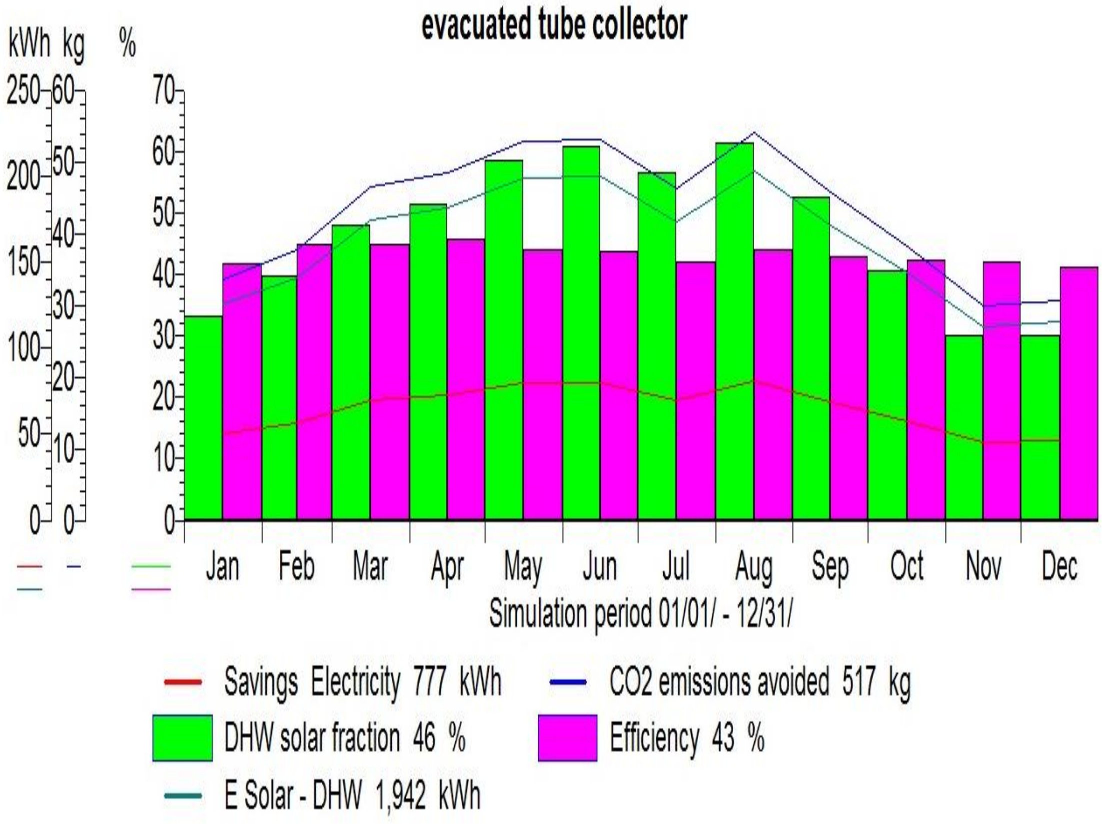

Figure 4.8 - Annual performance of Evacuated tube collector for Jan to Dec 2017

ETC effectiveness gave highest temperatures in May, June, July and August 2017 with highest efficiency of 69.9% at a collector area of 6.9m^2 and lowest efficiency of 43.19% at a collector area of 2.9m^2. ETC have the ability to utilise the smallest amount of light and convert it to heat thus warming water even without enough sunlight. This feature makes ETC the preferred in cold climates as compared to FPC.

4.4 Energy collected and efficiency of Evacuated tube collector

Different sizes of collectors efficiencies were compared and the results obtained using equations (1) and (3) as shown in table 4.7. The highest efficiency obtained is 69.9% and this represents a collector size of 2.9m^2 while the lowest is 43.2% representing a collector size of 6.9m^2. From the results obtained, it is evident that the collector area affects the overall efficiency of the collectors. This is due to a higher value of heat energy obtained and vice versa.

Table 4.7 - Heat intensity and efficiency of ETC solar water heater

Apartment	T_i(°C)	T_o(°C)	T_o - T_i	Mass flow	$Q_{u(kW)}$	Efficiency (η)
A	17.6	68	50.4	0.061375	12.99186	69.9
B	20	70	50	0.054125	11.36625	52.29
C	32.2	90	57.8	0.06325	15.35457	43.19
D	31	75	44	0.0635	11.7348	52.36
E	27	80	53	0.052875	11.76998	53.35

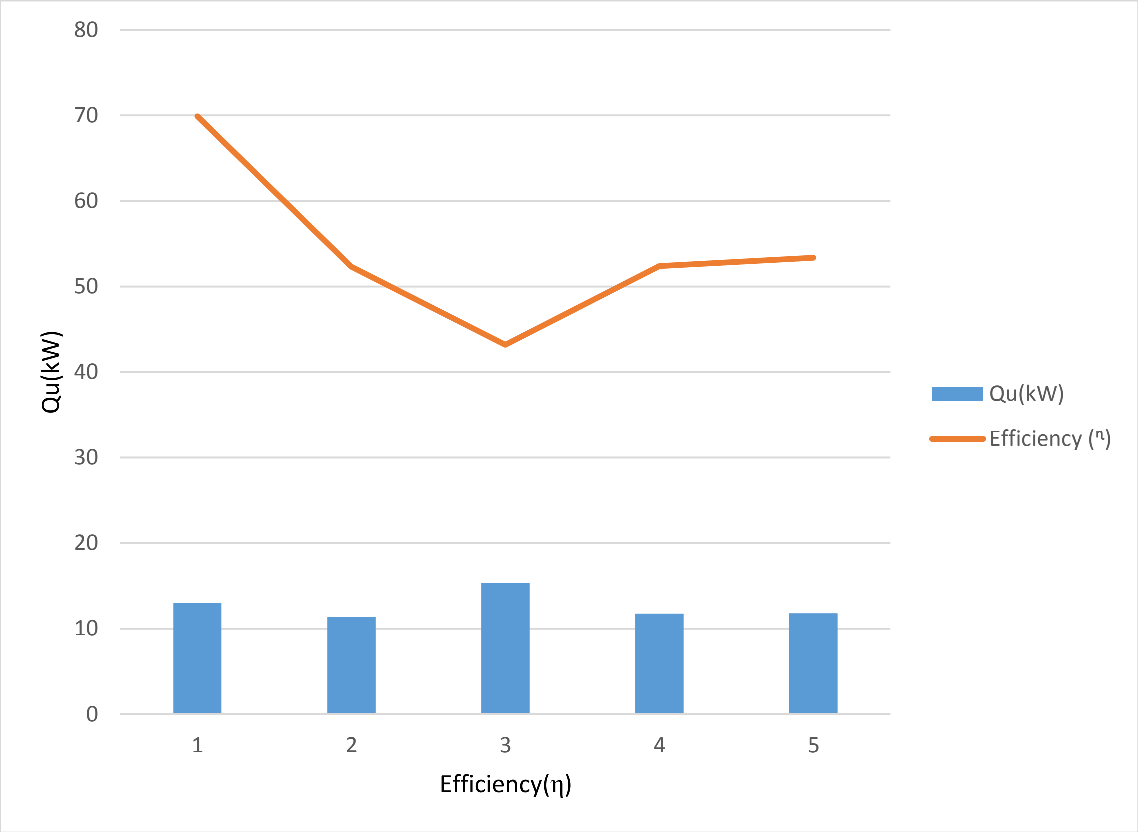

Figure 4.9 - Graph of Energy collected against Efficiency for ETC

From figure 4.7 it is evident that energy collected has an effect on the overall efficiency of the system. The higher the Energy collected the less the efficiency and vice versa. Temperature is a determinant of the Energy collected, when the temperature is high it results to a reduction in efficiency. From equation (3) then the main factor that affect the overall efficiency is collector area.

4.5 Energy collected and efficiency of Flat plate solar water heater collector

Table 4.8 - Heat intensity and efficiency of FPC solar water heater

Apartment	$T_i(^oC)$	$T_o(^oC)$	$T_o - T_i$	Mass flow	$Q_{u(kW)}$	Efficiency (ɳ)
A	17.4	39.35	21.95	0.04345	4.0057	21.6
B	22	48.63	26.63	0.04227	4.7277	20.5
C	27	54.38	27.38	0.0426	4.8988	19.14
D	25	57	32.00	0.0419	5.631	19.13

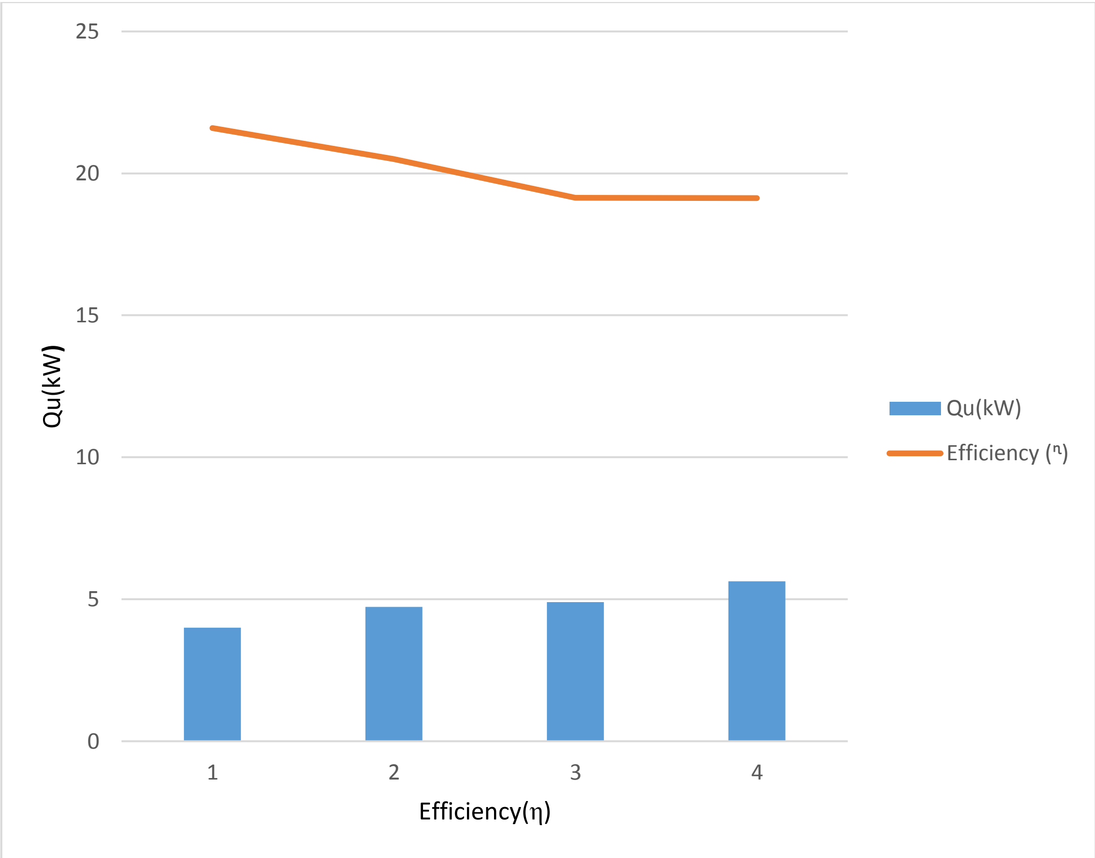

Figure 5.0 - Graph of Energy collected against Efficiency for FPC

From the figure 4.9 above it was found that the highest efficiency value is 21.6% and this was at a corresponding temperature difference of 21.95^0C while the lowest efficiency was 19.13% at a temperature difference of 32^0C. From this data it is clear that the efficiency of a flat plat is highest when the collector is colder as compared to when it has absorbed more heat.

4.6 Comparison between the ETC and FPC

Comparing the data from the above figure 4.8 and 4.9 for ETC and FPC respectively it is found that the evacuated tube collectors tend to have high efficiencies than Flat plate collectors. The appropriate point to measure the collector efficiency is at the average temperature for the water temperature range being considered and this is between 15^0C and 70^0C for domestic hot water systems. A fixed installation is the most typical installation due to its robustness, but in order to maximize the amount of collected solar heat, finding the optimum tilt angle and orientation is crucial. The flat plate collector is not able to track the sun, due to the fixed installation, and should therefore be orientated towards the equator when installed on the Nordic hemisphere.

4.7 Cost benefit analysis of Solar Water Heaters

This is a process by which business decisions are analysed. The benefits of a given situational or business related action are summed and then the costs associated with taking that action are subtracted.

This analysis involves analysing payback period of a project, Financial Analysis, depreciation, Accounting rate of return cash flow analysis and the net present value (NPV).

4.7.1 Payback Period

This is the length of time required to recover the cost of an investment. The payback period of a given investment or project is an important determinant of whether to undertake the position or project, as longer payback periods are typically not desirable for investment positions. It is calculated using the formula below: -

$$\text{Payback period} = \frac{\text{Capital cost} - \text{Cost of the system}}{\text{Monthly Savings}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots..5$$

Where; Monthly savings = energy demand per month (kWh) x Cost of electricity per kWh per month.

From the sampled households the following assumptions were made: -

- The Kenya Power and Lightning Company price per kWh is Ksh.12.75 for domestic consumption of between 50 to 1500kWh for the period between April to September 2017.
- Most of them use Lorenzetti showers of 2.5kW for a maximum of 15minutes showering both mornings and evenings.
- They use electric kettle of 2.5kW

Therefore for a household of 5 people the average daily hot water load =10.63kWh.

In a month assuming a 30-day month, average hot water load=318.75kWh.

The following is a breakdown of all the annual costs incurred for installing a single ETC solar water panel. Since solar water heaters collectors comes in different sizes like 150L, 200L and 300L and each system varies in cost of purchase, then the calculations below only reflect a 300L evacuated tube system. Annual revenue is derived from the savings on monthly basis and also to note is that different systems have different savings.

Table 4.9 – Annual expenditure for installation of Evacuated Tube Collector solar water heater

Item	**Cost (Kshs.)**
Cost of Panel(300L)	155,000
Labour	10,000
Pipes	5,000
Water Tank	15,000

Applying equation (4) above then;

Payback period for a load of 318.75kWh is:

$$\text{Payback period(in months)} = \frac{175{,}000}{318.75x12.75}$$

=43.06 months

=3.59 years≈ 4 years

For Flat plate solar water heater collector, using the same assumptions and applying equation (4) above with a price of kshs.85, 000.

Then Payback period will be;

$$\text{Payback period(in months)} = \frac{85{,}000}{318.75\text{x}12.75}$$

= 20.9 months

=1.74 years≈2 years

Cumulative present worth factor

$$P_a = \frac{1 - X^n}{1 - X} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.6$$

Where P_a is cumulative present worth factor

X is inflation rate in Kenya

n is useful no of years of the solar water heater

r is the discount rate

But

$$x = \frac{1.05}{1.15}$$

$$P_a = \frac{1 - 0.913^{20}}{1 - 0.913}$$

$$P_a = 9.633$$

Cost of electricity for showers assuming a maximum of 15 minutes showering for one person

$$3.125 \times 30 = \text{Kshs. } 93.75$$

Electrical cost for first year will then be

$$= 12 \times 93.75 \times 2.5$$

$$= \text{Kshs.} 382.5$$

Therefore; Present worth will be

$$P_w = P_a \text{x} \text{Cost of electricity} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

Hence $P_w = 9.633 \times 382.5$

$$= \text{Kshs.} 3684.6$$

4.7.2 Financial Analysis

This is the process of evaluating businesses, projects, budgets and other finance related entities to determine their performance and suitability. This analysis is used to analyse whether an entity is stable, solvent, liquid or profitable enough to warrant a monetary investment. This analysis was done using T-SOL software and the result is as shown below

Financial analysis parameters	
Life span:	20 Years
Interest on capital:	2.5 %
Reinvestment return:	2.5 %
Energy cost escalation rate:	2.0 %
Running cost escalation rate:	1.0 %
Financing	
Total investments:	1,504 $
Subsidies:	0 $
Loan capital:	0 $
Remaining investment:	1,504 $
Running costs in first year:	0 $
Savings in first year:	237 $
Financial analysis	
Cost of solar energy:	0.036 $/kWh
Capital return time:	6.0 Years
Amortization period:	6.6 Years
Profitability	
Return on assets:	382.6 %
Return on equity:	382.6 %
Internal rate of return rate, IRR:	16.67 %
Net present value:	2,909 $
Reinvestment premise	
Profit:	5,727 $
Modified internal rate of return, MIRR:	8.17 %

The financial analysis can also be analysed in form of a graph showing cost of operation throughout the useful years of the solar water heater panel, profits and remaining investment as shown in the graph below.

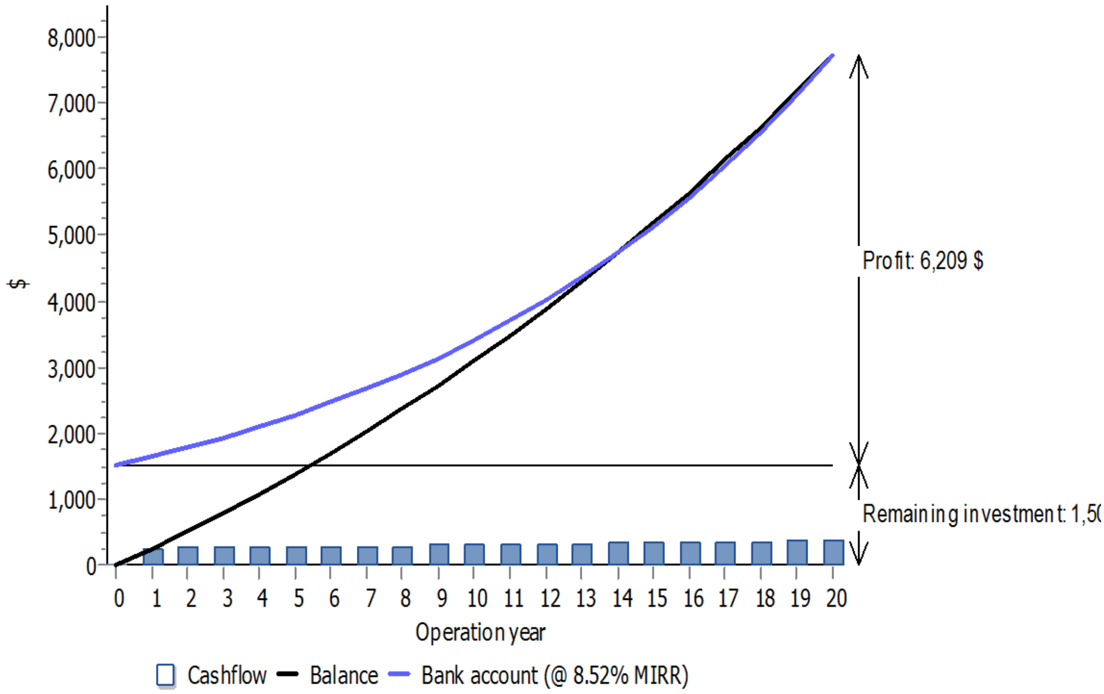

Figure 5.1 - Graph of cost of the panel against useful operation years of the collector

The graph in figure 5.1 shows the collector panel cost against its useful operational years. If the cost of a panel is $1,504 and has a lifespan of 20years, then the savings for this particular panel will be $237 for the first year. Therefore, the reinvestment profit after 6 years of operation will be $5,727 from the 6th year onwards until the end of its useful year

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

This chapter gives the conclusions and recommendations derived from the study carried out.

5.1 CONCLUSIONS

Results from the research revealed that for FPC, the highest temperatures were attained at 2.00 pm and it gave an average temperature of 67^0C and the lowest temperature was at 9.00 am and it gave temperatures of 42^0C for a collector area of $4.6m^2$ and orientation of 45^0. For a collector area of $2.9m^2$ and orientation of 32^0, the highest temperatures was 50^0C at 2.00 pm while the lowest was 26.5^0Cat 9.00 am. ETC's gave the highest average temperature of 90^0Cwhich was attained at 2.00pm and the lowest was 79.5^0C at 9.00 am for a collector area of $6.9m^2$ and collector orientation of 40^0. For a collector area of $2.9m^2$ and orientation of 30^0, the highest average temperature was 68^0Cwhich was attained at 2.00pm and the lowest was 30.4^0C at 9.00 am.

This study also reveals that FPC effectiveness on simulating the thermal performance on T-SOL software shows that the highest temperatures were attained in January, February, November and December 2017 and its highest efficiency was 21.6% for a collector area of $4.6m^2$and the lowest efficiency was 19.13% for a collector area of $2.9m^2$. ETC effectiveness gave highest temperatures in May, June, July and August 2017with highest efficiency of 69.9% at a collector area of $6.9m^2$ and lowest efficiency of 43.19% at a collector area of $2.9m^2$.

Cost benefit analysis of the SWH systems were done at a price per kWh of KES 12.75 for a consumption of 50 to 1500kWh for May to September 2017. The price of FPC of KES 85,000 gave payback period of 2 years and changing the price to KES 175,000 for ETC gave a payback period of 4 years.

5.2 RECOMMENDATION

From research conducted, it is recommended that angles of 45^0 for FPC's and collector area of $4.6m^2$ be considered as they have shown to give temperatures of as high as 67^0C and lowest of 42^0C on a good sunny day. ETC's optimum angles recommended is $40^0$and this angle gives highest temperatures of 90^0C with lowest of 79.5^0C at collector area of $6.9m^2$. These temperatures are impressive and will go a long way in saving electricity consumption that could otherwise be used in water heating.

It is also recommended that in order to attain higher water temperatures, lagging is important and therefore most of the systems need to have proper lagging as most of them already installed are not or either partly lagged

This research was carried out in Nairobi County and since Kenya is divided into several climatic regions as indicated in appendix A, it is recommended that future works be carried out on other regions since every climatic region has its own characteristics which do hinder the performance of SWH.

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APPENDICES

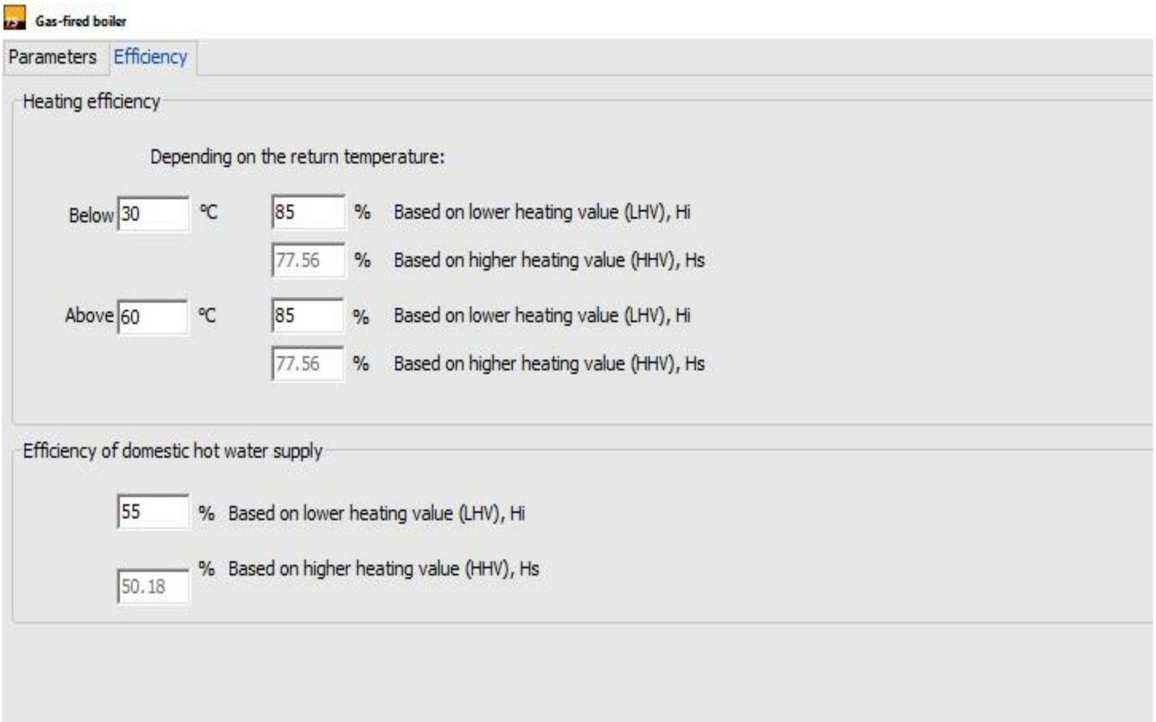
Appendix I: Kenya climatic zoning

Climatic zone	Characteristics
Coastal equatorial climate	This region has no dry season but has a well-developed double maximum rainfall in May and October. There is high average temperatures and humidity throughout the year. The Kenyan coast differs from the equatorial climate being well known for its high annual rainfall totals in that it receives much lower totals. The coastal region records highs of 31.1^0C and lows of 26^0C, representing a very small range.
Tropical highlands climate	The climate is cooler than a tropical continental climate. The amount of rainfall received at different places depends on the position of the station in relation to the rain-bearing winds. This region has the best climate in the country. Day temperatures are cool and nights may be chilly. Temperatures in this region fluctuates between highs of 28^0C in January and lows of 8^0C in July
Lake Victoria basin equatorial climate	The rainfall totals in the region show considerable variations and are in any case much lower than a typical equatorial climate. The enclosed basin of Lake Victoria tends to increase temperatures, although the lake itself exerts a cooling

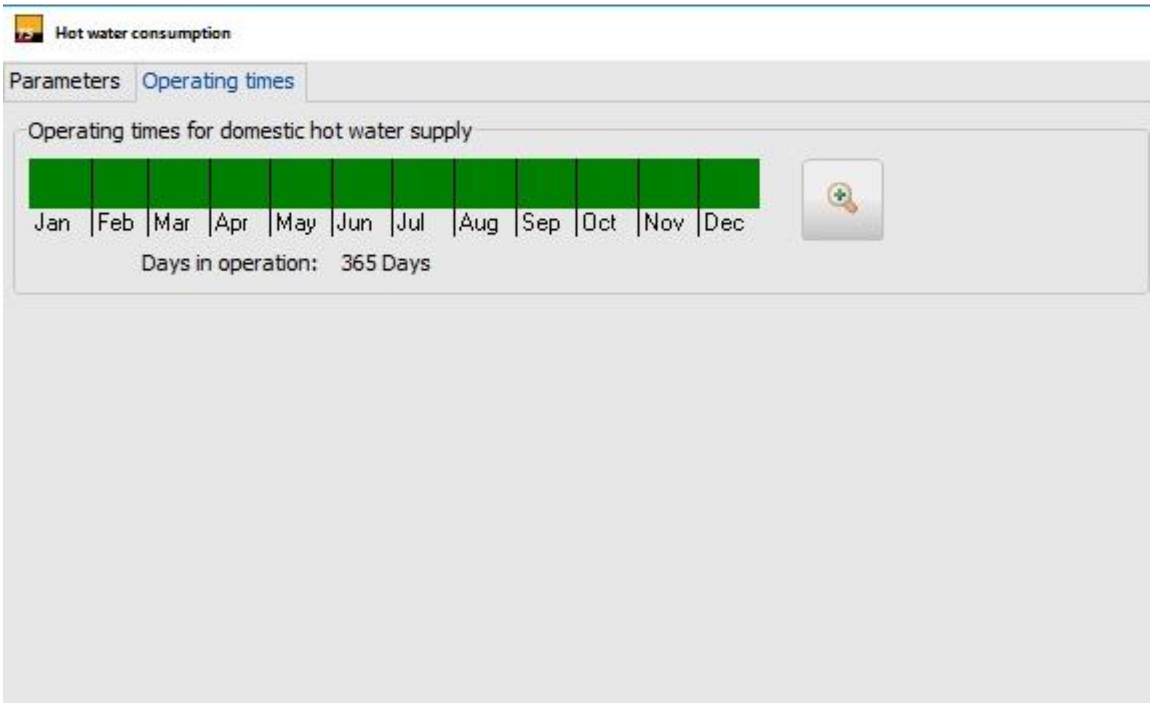
	influence on the surrounding areas. Temperatures are as high as 35^0C
North western equatorial climate	This is a continuation of the climate of Eastern and North Uganda. High relief lowers the temperature in parts of the region
Tropical climate of Narok and Southern Taita/Kwale	This is part of the tropical climate that dominates the central mainland of Tanzania. The high relief of some localities exerts a cooling effect so that taken altogether, the climate here is more tolerable than the semi-desert climate of eastern Kenya.
Eastern tropical continental semi desert climate	This vast region receives <500 mm of annual rainfall. The mean annual temperature is between 22 and 27 ^0C with a very wide daily range of about 11 ^0C. The skies are generally clear and great variations in the mean annual rainfall can be expected.
Desert climate of Central Northern Kenya	A considerable stretch of northern Kenya receives <250 mm of rainfall and its climatology may be regarded as desert. The aridity of this area is a continuation of that of Arabia. In this region, the skies are cloudless and visibility is only hindered by sandstorms.

Appendix II: T-SOL 2017-R2 Software programme

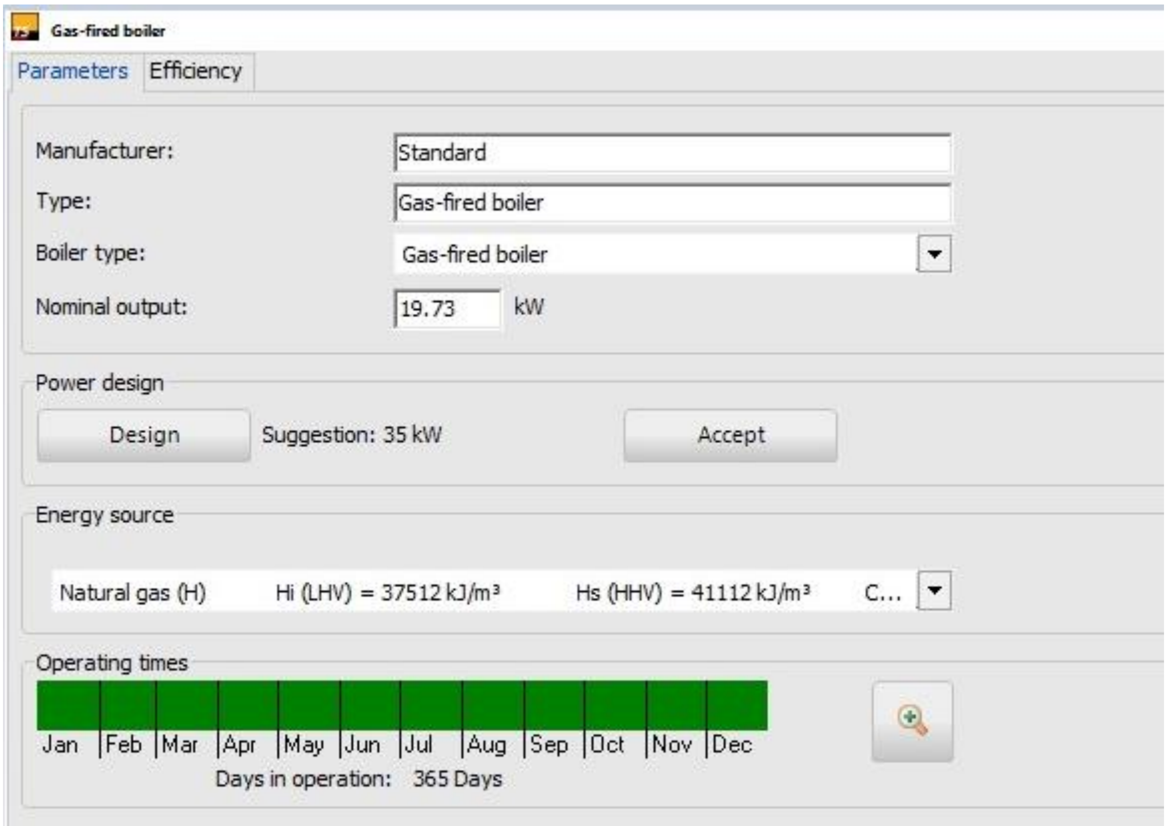
System heating efficiency



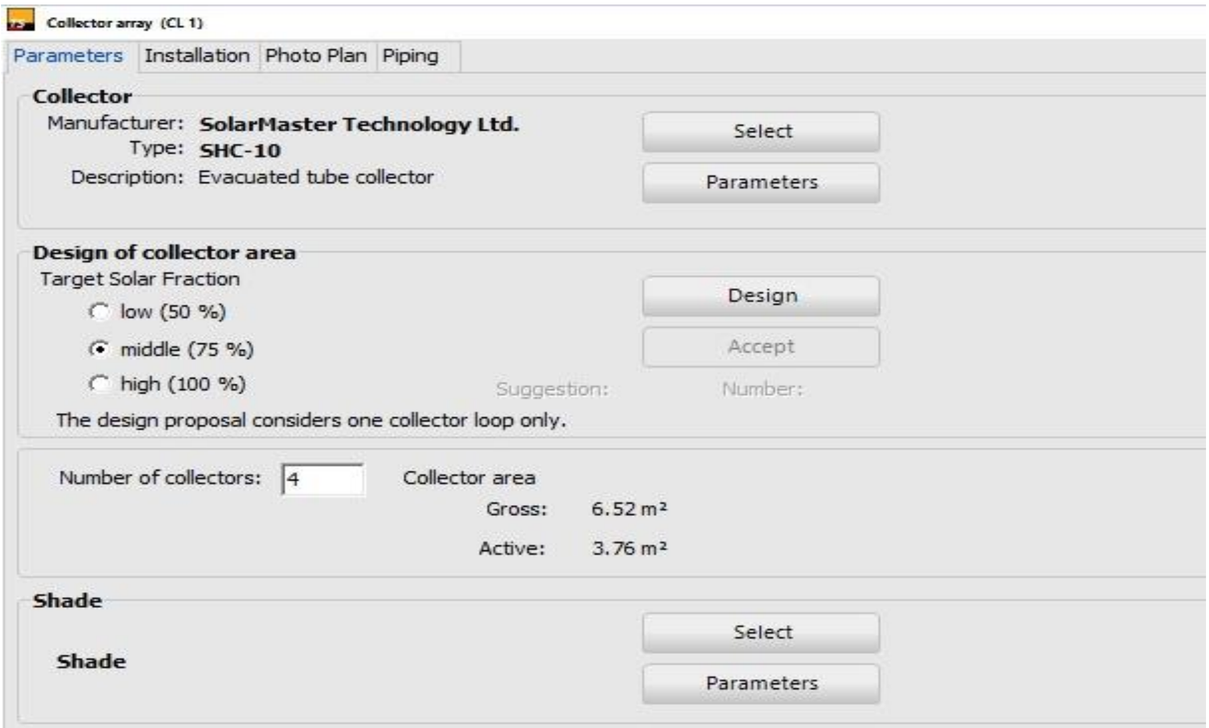
Domestic hot water supply operating times



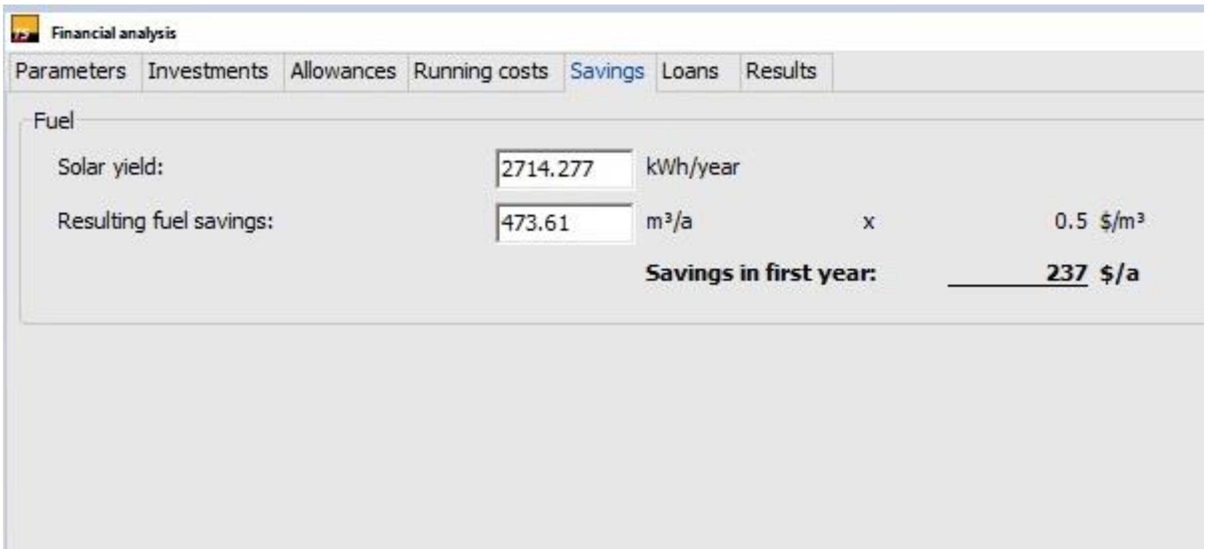
Collector specifications



Evacuated tube Collector specifications



Solar collector annual savings



Appendix III: Solar water heaters arrangements