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Evaluating the Performance of Solar Water Heaters in Nairobi County, Kenya

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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.

This study evaluates the performance of solar water heating in Nairobi County Kenya which 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. Nairobi has a population 3,375,000 and its population has been increasing steadily from 3,138,295 inhabitants in 2009 to 3.36million in 2011.

The water inlet temperature was measured using Infrared thermometer between 9.00 and 16.00 hours with variation of one hour between the duration, monitoring of the water outlet temperatures in a temperature display unit maintaining the one-hour duration between the stated times. Solar insolation was measured using the Hukseflux thermal sensors application software installed on iPhone and average data recorded daily. Finally, T*Sol software was used to analyze the annual performance of flat plate and evacuated tube solar collectors.

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.

From this study it was noted that performance of solar water heaters is impressive and are giving temperatures as high as upto 90^{0}C on a clear sunny day. On a cloudy day the SWH still produce water at temperatures higher than 35^{0}C.

This study also reveals that collector area is of importance in attaining higher water temperatures and the larger the area the higher the temperature and vice versa, Vacuum tubes performance is better compared to flat plates since vacuum tubes have the capability to produce warmer water even during cloudy climates as compared to flat plates but flat plates have good energy picking when there is sunlight.

I. Introduction

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 O, 2011)

Solar thermal 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 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.

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

I.1 Solar water heating

Solar water heating (SWH) is the conversion of sunlight into heat for water heating using a solar thermal collector. A variety of configurations are available at varying cost to provide solutions in different climates and latitudes. SWHs are widely used for residential and some industrial applications.

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. The purpose of using a solar DHW system is to convert the solar radiation into thermal energy, and then to use it for domestic hot water heating, thus reducing the over dependence on and consumption of conventional energy. Recently, environmental issues have led to an even greater interest in solar DHW systems (Selfa, 2015).

I.2 Solar collectors

A solar collector, the 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 use later (at night or cloudy days) (Tian et.al, 2012).

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.

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.

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.

II. Methodology

Various instruments, methods and materials were used in evaluating the performance of solar water heaters in Nairobi County. Proportional random samples of the premises and households were selected from each sub-county. Methods used in carrying out this study involved Monitoring of outlet temperatures from the collector and this involved taking readings on the temperature display unit between 9.00 to 16.00 hours with intervals of 1hr each.

Temperature 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 9.00 and 16.00hrs with intervals of 1hr each. Angle measurement was done 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.

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.

III. Results, Analysis and Discussion

III.1 Monitoring of Installed Flat plate solar water heater collector

In this study 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 1: Collector area against temperature for flat plate collectors

	Collector Area/Collector Outlet Temp in ^oC			
Time	Collector Area 2.9 m^2	Collector Area 3.6 m^2	Collector Area 4 m^2	Collector Area 4.6 m^2
9	26.5	30	40	42
10	34	42	48	53
11	36.3	46	54	60
12	38	48	56	60
13	40	57	60	65
14	50	62	64	67
15	48	55	60	59
16	42	49	53	50

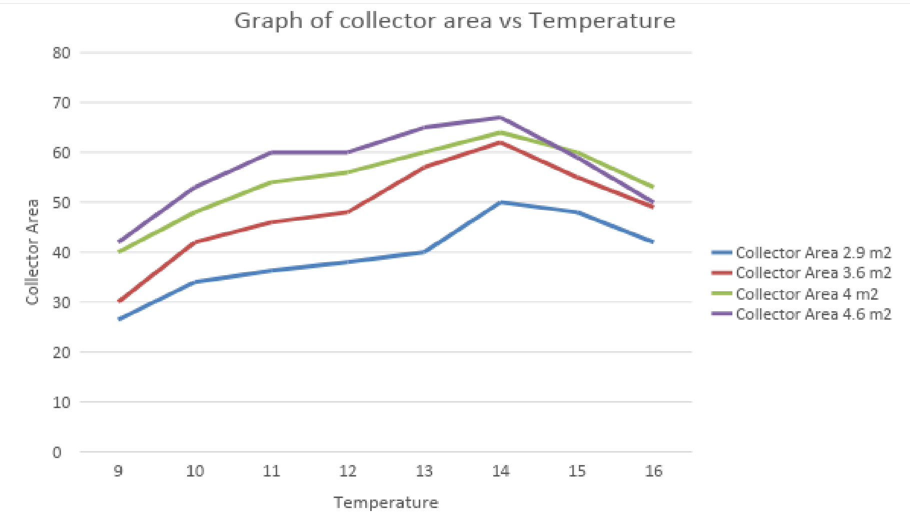

Figure 1: Graph of temperature against collector area for flat plat collectors

The figure 1 above illustrates the temperatures of different flat plate collector sizes from 2.9,3.6,4 and 4.6m^2. From the graph it is seen that the smaller 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. There is also a sudden rise in temperature from 9.00hours to 11.00 hours 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 hours 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.

3.2 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. Each tube consists of a thick glass outer tube and a thinner glass inner tube, (called a "twin-glass tube") or a "thermos-flask tube" which is covered with a special coating that absorbs solar energy but inhibits heat loss. 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 2 - Collector area against temperature for evacuated tube collectors

	Collector Area/Collector Outlet Temp in ^{o}C				
Time	Collector Area 2.9 m^2	Collector Area 3.6 m^2	Collector Area 4 m^2	Collector Area 4.6 m^2	Collector Area 6.9 m^2
9	30.4	35	43.8	47	79.5
10	32.7	40	45	50	80
11	35.3	45	48	57	81.3
12	39	60	60	62	84
13	45	67	65	69.4	85.9
14	68	75	78	75	90
15	65	73	75	70	85
16	64	60	60	65	74.6

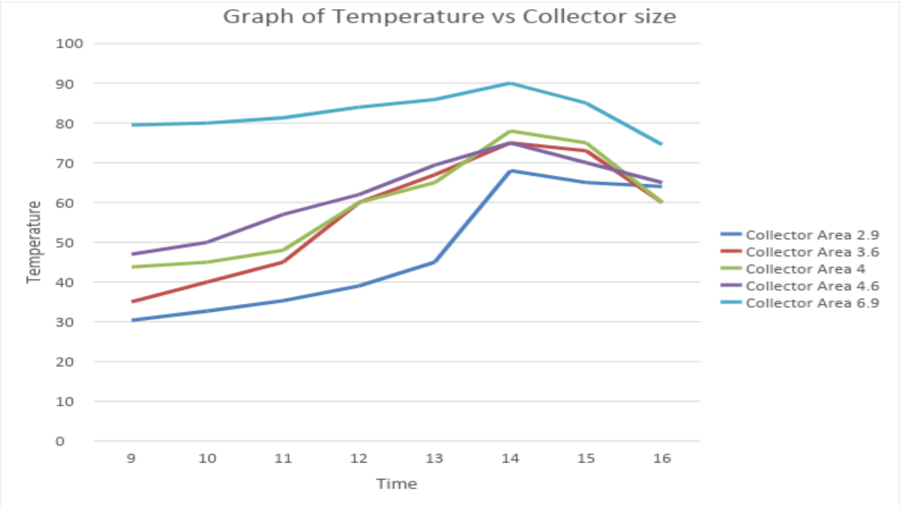

Figure 2-Graph of temperature against collector area for ETC.

The graph above shows results obtained by monitoring outlet temperatures of different vacuum tubes collector sizes of 2.9 m^2, 3.6 m^2, 4 m^2, 4.6 m^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^{0}C at 14.00 hours. The collector having the smallest area among the ones monitored is 2.9m^2 which has a temperature of 68^{0}C at 14.00hours. 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 collectory 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.

It is evident that temperature increase is dependent on time. As time advances then the insolation increases and subsequently increase in temperature with highest values recorded at 14.00 hours in all the collector sizes and then the temperature starts dropping from 15.00 hours up to 16.00 hours. 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.

III.2 Tilt angle and corresponding temperatures for FPC's

Table 3- Tilt angle and corresponding temperatures for Flat plate collectors

	Tilt Angle/Collector outlet Temperature in ^{o}C			
Time	32^{0}C	35^{0}C	40^{0}C	45^{0}C
9	26.5	30	40	42
10	34	42	48	53
11	36.3	46	54	60
12	38	48	56	60
13	40	57	60	65
14	50	62	64	67
15	48	55	60	59
16	42	49	53	50

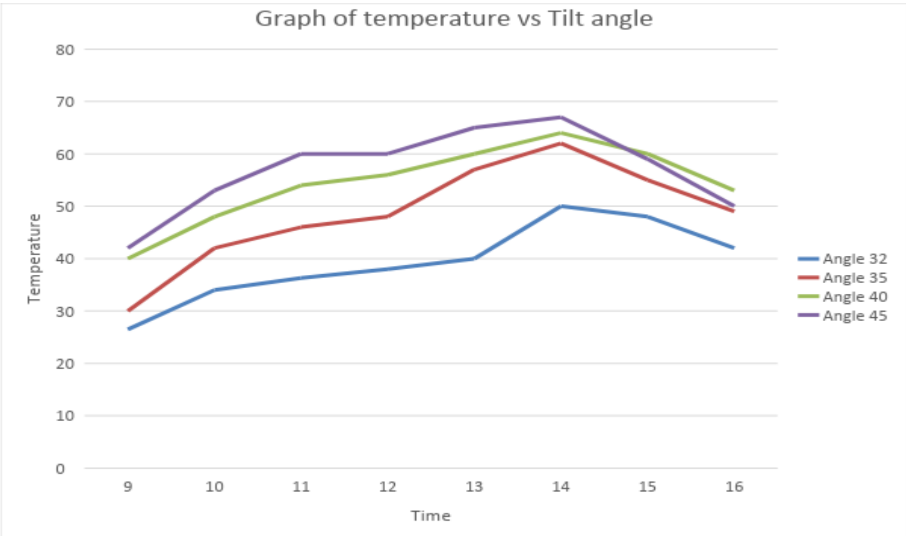

Figure 3- Graph of Temperature against tilt angle for flat plate collectors

The figure 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 32,35,40 and 45^0. In this case at 32^0 it was found that the highest temperature recorded was 50^{0}C and this value was realized at 14.00hours while the lowest temperature at this orientation was 26.5^{0}C at 9.00 hours. The highest temperature was at 45^0 and at this angle the highest recorded temperature was 67^{0}C and at this angle the lowest temperature value was 42^{0}C at 9.00 hours.

The performance of Flat plate collectors largely depends on the orientation and the most suitable angle in this case is 45^{o}C 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 study conducted by (Sivakumar et.al, 2012) he found out that the maximum outlet temperatures were recorded at 13.00 hour and the outlet temperature reduced after 13.00 hour until 17.00 hour which is almost as the results obtained in this study which shows that the temperature reduces from 15.00 hours upto 16.00 hours.

3.3 Tilt angle and corresponding Temperatures per apartment for ETC's

Table 4 – Tilt angle and corresponding temperatures for evacuated tube collectors

	Tilt Angle/Collector Outlet Temp in ^{o}C				
Time	30^{0}C	32^{0}C	35^{0}C	40^{0}C	45^{0}C
9	30.4	35	43.8	79.5	47
10	32.7	40	45	80	50
11	35.3	45	48	81.3	57
12	39	60	60	84	62
13	45	67	65	85.9	69.4
14	68	75	78	90	75
15	65	73	75	85	70
16	64	60	60	74.6	65

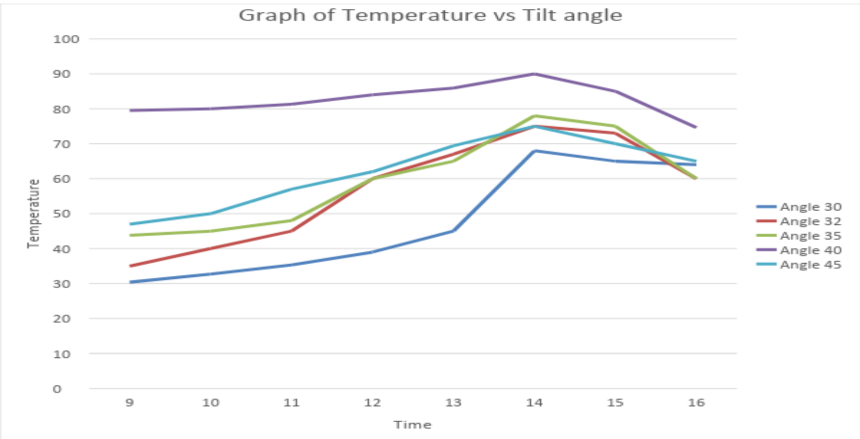

Figure 4 -Graph of temperature against the tilt angle for ETC

The figure 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 30^0,32^0,35^0,40^0 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 14.00hours while the lowest temperature at this orientation was 30.4^0C at 11.00 hours. The highest temperature was at 40^0 and at this angle the highest recorded temperature was 90^0C and at this angle the lowest temperature value was 74.6^0C at 16.00 hours. From this study, 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 study conducted then at 14.00 hours 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.

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, vacuum tubes 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. 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).

3.4 Energy collected and efficiency of Evacuated tube collector

Different sizes of collectors efficiencies were compared and the results obtained using equations (i) and (iii) as shown in table 4.6. 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 5 - 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 ($^\eta$)
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

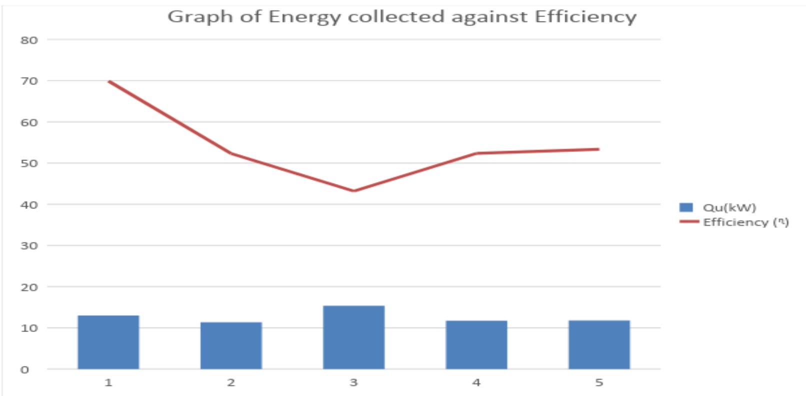

Figure 5 - Graph of Energy collected against Efficiency for ETC

From figure 5 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 (iii) then the main factor that affect the overall efficiency is collector area. The less the area then the more the efficiency and vice versa.

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

Table 6 - 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 (η)
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

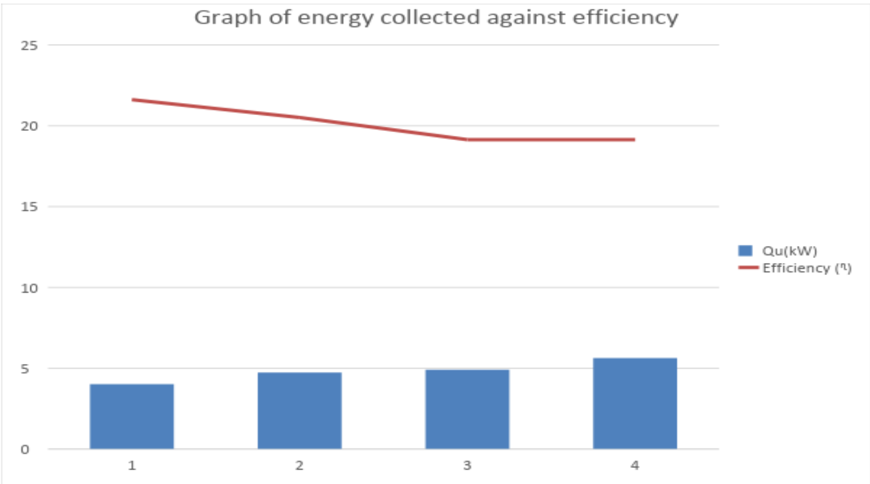

Figure 6 - Graph of Energy collected against Efficiency for FPC

From the figure 6 above it was found that the highest efficiency value is 21.6% and this was at a corresponding temperature difference of 21.95^{0}C while the lowest efficiency was 19.13% at a temperature difference of 32^{0}C. 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.

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^{0}C and 70^{0}C 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.

IV. Conclusions

Results from the study shows that most of the apartments, institutions, hotels and residential have not installed solar water heaters due to lack of information regarding the same. Those already installed have managed to reduce electricity cost and overdependence in electricity as the solar water heating system depend majorly on the available insolation which the study reveals are abundant and secondly on the daily water heating demands of a particular individual. The higher the daily water heating demand, the larger solar water heating system and hence the higher the investment cost. Calculation of the estimated costs of installations show that solar technologies are still very expensive despite the government effort to reduce the prices.

From this study it was noted that performance of solar water heaters is impressive and are giving temperatures as high as up to 90^0C on a clear sunny day. On a cloudy day the SWH still produce water at temperatures higher than 35^0C.

Most premises are installed majorly with evacuated vacuum tubes-non pressurised and flat plate collectors and these systems have played a major role in reducing the emissions into the environment and thus reducing pollution.

This study also reveals that collector area is of importance in attaining higher water temperatures and the larger the area the higher the temperature and vice versa, Vacuum tubes performance is better compared to flat plates since vacuum tubes have the capability to produce warmer water even during cloudy climates as compared to flat plates but flat plates have good energy picking when there is sunlight.

Also the orientation angle of the collectors is very important as this determines the sunlight collected at different times of the day. Therefore, proper orientation will ensure that the collector always receives sun's rays most part of the day.

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