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Analysis of a Solar Thermal Based Hot Water System for a Non-Residential Application

M.A. Aslam
Sri Lanka Institute of Information Technology, SLIIT Malabe Campus, Colombo, Sri Lanka
asadd.aslam21@gmail.com

ABSTRACT

Industries in Sri Lanka rely heavily on the use of hot water for their day-to-day applications. Industries such as hotels and hospitals utilise electrically powered geysers, while industries such as wood treating factories, garment industries, and paper manufacturing industries rely on boilers to obtain heated water. The rising cost of electricity production and the pollution associated with current power generation technologies in Sri Lanka have led to a need for a water heating framework which focuses on harnessing renewable energy. Since Sri Lanka is located in close proximity to the equatorial belt, solar thermal water heaters were selected as one of the most viable options. In this study, a hospital was selected as the base scenario onto which a solar water heating framework was to be designed for. The framework focused on the feasibility of three collector types, *i.e.*, Flat Plate Collector, Evacuated Tube Collector and Parabolic Trough Collector. Initially theoretical efficiencies of each collector type were determined for the average annual solar radiation in Sri Lanka. Finally, RETScreen simulation software was used to perform sizing analysis of each water heating system, analyse each systems financial viability and analyse the reduction in annual Greenhouse Gas (GHG) emissions.

KEYWORDS: *Solar radiation, water heater, solar collector, flat plate, evacuated tube, parabolic trough, efficiency, RETScreen.*

1 INTRODUCTION

The continuous advancement in technology and the increasing growth of the global population has led to an increase in the demand for energy. According to statistical data of world energy published by bp it was discovered that the energy demand for the year 2021 had increased by 5.8%. A large portion of this global energy demand is currently obtained via fossil fuels. According to the figures released, fossil fuels accounted for about 82% of the global energy usage for the year 2021, while the remaining 18% of the global energy requirement was catered via renewable and alternative energy sources such as Hydroelectricity, Nuclear energy, Solar and wind energy. Fossil fuels are supplied to the market in three types, they are coal, natural gas and oil. 36% of the global energy requirement was catered to by Coal, while natural gas and oil both supplied 23% each of the global energy requirement (bp 2022). The major drawback when utilising fossil fuels is the adverse effect it has on the environment. The extraction, refining and end use stages of these energy sources collectively pollute the environment. Since the end use of most fossil fuels is to obtain energy via combustion, it has the most severe impact of all stages (Barbir et al. 1990). Fossil fuels often contain impurities in its chemical composition, upon combustion oxides of carbon, nitrogen and sulfur may be formed and released into the atmosphere (Garrick 2008). The release of these gases into the atmosphere may lead to phenomena such as acid rain, ground-level ozone and global warming. Carbon dioxide, which is a greenhouse gas, is the main contributing factor towards global warming as it has the ability absorb infrared radiation incident on the earth, eventually leading to an increase in the atmospheric temperature (Gupta Ram B. 2010). In the year 2021 a total of 33.9 $GtCO_2e$ (gigatonnes of CO_2 equivalent) was emitted from energy, which is an increase of 5.9% from the preceding year (bp 2022).

In addition to the adverse effects caused by using fossil fuels, another factor that hinders the use of fossil fuels as an energy source is its cost. The cost of oil, natural gas and coal increased sharply in

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the year 2021. According to the statistical figures released, the price of oil rose to 70.91 USD/ barrel in 2021 which was the highest it had reached since the year 2015. Coal was priced at approximately 145 USD / tonne in the Asian region for the year 2021. Natural gas prices experienced the sharpest increase in price with a listing of 18.6 USD / mmBTU in the Asian region, this was a threefold increase of its price in the preceding year and the highest price ever recorded since 2014 (bp 2022).

Industries in Sri Lanka rely heavily on the use of hot water for their day-to-day applications. Industries such as hotels and hospitals utilize hot water for applications such as cleaning laundry, culinary purposes, maintenance purposes and sterilization of surgical equipment in the case of hospitals. The typical temperature of water required for these purposes may vary from 45 – 70 °C (Jayasinghe 2016). Electrical water heaters are typically used by these industries to obtain the required level of heated water. On the contrary, industries such as wood treating factories, garment industries, brewing industries and paper manufacturing industries require relatively higher temperatures of water and on occasions require steam to drive the heavy-duty machinery available at the workshop. The required level of heated water or steam required for these processes are generally obtained from boilers. The feed fuels for these boilers are usually coal, furnace oil or biomass fuels (Siriwardena et al 2020). 49% of the total electricity generated in the year 2021 was accounted for by fossil fuels (*i.e.* coal and oil), while the remaining 51% of the total electricity generate was accounted for by renewable sources of energy. According to a study published by *Withanaarachchi et al*, it was mentioned that 95 % of the total electricity requirement of Sri Lanka was catered to by hydro power plants alone in the year 1995. The figure reduced dramatically to 46.56% in the year 2010 and this was attributed to the increasing requirement of domestic electricity and the rapid development of the industrial sector of the country (Withanaarachchi et al 2014). The downward trend in the ability of the hydro power plants to cater to the demands of the Sri Lankan electricity grid can be seen in the figure above as it was only able to account for 34% of the electricity generated in the year 2021. An increase in the electricity tariff took place in the year 2022, nearly eight years since the last revision of the electricity tariff, in order to account for the increasing cost of producing each unit of electricity ("Explainer: Sri Lanka's electricity tariff hike and how it works | Economynext" 2022). The location of Sri Lanka in close proximity to the earth's equatorial line provides huge potential for extraction of useful solar energy (Renne et al. 2003).

The work carried out in this study aimed at providing a generalised framework that could be adhered to by industries in Sri Lanka that intend to switch to solar water heaters to fulfill their desired hot water requirement. A base case scenario was to be included in the framework, this was done in order to facilitate environmental, economic and physical parameters related to Sri Lankan context. The base case scenario was to be selected from industrial sectors such as a textile industry, hospital or hotel. Theoretical collector efficiencies were to be determined along with the finances involved when setting up each collector type, in order to allow the industrial organisation to make an informed decision when selecting its preferred collector type. Finally, the framework was to provide guidelines required to set up a hot water storage tank, which would serve as the central distribution point of heated water to the required loads of the industry. The process of setting up an auxiliary heating device was also included in the framework to account for the occasions when the required temperatures could not be obtained via solar collectors alone.

2 MATERIALS AND METHODS

It was decided to select a hospital as the industrial application to be analysed for this research project. Kings Hospital, located in Colombo, Sri Lanka was selected as the base scenario to determine the general hot water requirements of an industrial application. Initial analysis of the hospital revealed that the hospital did not contain a centralized water heating system to provide its daily hot water requirement. Instead, the hospital utilized electrically powered geysers to supply its daily hot water requirement. Daily hot water requirements were to be acquired from the said hospital and the number of panels required to provide the required heating and the size of storage tank were to be determined accordingly. The specifications of solar collectors, such as the capacity, cost of installation and the physical dimensions of collectors were to be obtained from suppliers present in the local market where applicable. Information for flat plate collectors were obtained from Alpha Thermal Systems Pvt Ltd while information for evacuated tube collectors were obtained from JFA Sunbird Renewable Energy Pvt

Ltd which are companies that manufacture the said panels in Sri Lanka. However, for the parabolic trough collector, it was decided to use 'Absolicon', a company based in Sweden, as the supplier.

2.1 Theoretical Efficiency Equations of Each Collector Type

The thermal efficiency of a flat plate collector was determined based on predefined equations of heat gain. For the purpose of analysis, it was assumed that the collector being analysed had a unit surface area (*i.e.*, $A_c = 1$ m^2). The equations for efficiency of a collector under steady state conditions obtained from (Duffie and Beckman 2013) are shown below.

$$\eta = \frac{\dot{Q}_u}{I_T A_C} \quad (1)$$

Where, η refers to the collector efficiency, $\dot{Q}_u$ is the useful heat gain by the collector, I_T is the total radiation incident on the collector (W/ m^2), A_C is the surface area of the collector (m^2). The useful heat gain by a collector can be defined as follows (American Society of Heating and Air-Conditioning Engineers, 2019),

$$\dot{Q}_u = A_C F_R I_{T\theta} (\tau\alpha)_\theta - A_C F_R U_L (T_{fi} - T_a) \quad (2)$$

Where, F_R is the collector heat removal factor, $I_{T\theta}$ i s the total irradiation of collector (W/ m^2), τ is the transmittance of the flat plate cover, α id the absorbance of the plate, θ is the Incident angle (°), U_L is the overall heat loss coefficient (W/ m^2 °C), T_{fi} is the fluid inlet temperature (°C) and T_a refers to the Ambient temperature (°C).. The equation for Collector heat removal factor (F_R) for a flat plate collector can be defined in terms of Collector Flow Factor (F'') and Collector Efficiency Factor (F') as follows.

$$F_R = F'' \times F' \quad (3)$$

The equation for Collector Efficiency Factor F' is defined as follows,

$$F' = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L[D + (W-D)F]} + \frac{1}{c_b} + \frac{1}{\pi D_i h_{fi}}\right]} \quad (4)$$

Where, W is the distance between the tubes (m), D is the tube diameter (m), D_i is the internal diameter of the tube (m), c_b is the Bond conductance, h_{fi} is the heat transfer coefficient between the fluid and tube wall (W/m^2 °C) and F refers to the fin efficiency factor. Bond conductance can be defined in terms of thermal conductivity of the bond (k_b /W/m^2 °C), bond width (b /m) and average bond thickness (γ /m)

$$c_b = \frac{k_b \times b}{\gamma} \quad (5)$$

The Fin efficiency factor (F) was defined as follows,

$$F = \frac{\tanh[m(W-D)/2]}{m(W-D)/2} \quad (6)$$

Where the term m is defined by the following equation.

$$m = \sqrt{\frac{U_L}{k\delta}} \tag{7}$$

Where δ refers to the thickness of the plate and the other symbols have the same definition as described earlier. The equation for Collector Flow Factor F'' is defined as follows,

$$F'' = \frac{\dot{m}C_p}{A_C U_L F'}\left[1 - \exp(-\frac{A_C U_L F'}{\dot{m}C_p})\right] \tag{8}$$

An expression for the efficiency of an evacuated tube collector has been determined experimentally and can be defined as follows (Calise Francesco, 2019).

$$\eta = \eta_0 IAM_b + \eta_0 IAM_d - c_1\frac{(T_{fi} - T_a)}{I_T} - c_2\frac{(T_{fi} - T_a)^2}{I_T} - c_3 u\frac{(T_{fi} - T_a)}{I_T} + c_4\frac{(E_L - \sigma {T_a}^4)}{I_T} - c_6\frac{1}{I_T}\frac{dT_m}{dT} - K_d u \tag{9}$$

Where $\eta_0, c_1, c_2, c_3, c_4$, c_6 and K_d are parameters which define each solar thermal collector, these values are generally supplied by the manufacturer. The terms IAM_b and IAM_b collectively represent the incident angle modifier in the case of beam and diffuse radiation respectively. u represents the wind speed, G is the irradiation incident on the surface, E_L is the emissivity of the collector and σ represents the Stefan-Boltzmann constant (Calise Francesco, 2019). A simplified equation for evacuated tube was developed in a study conducted by (Hayek et al. 2011).

$$\eta = \eta_0 - c_1\frac{(T_{fi} - T_a)}{I_T} - c_2\frac{(T_{fi} - T_a)^2}{I_T} \tag{10}$$

Predefined values for the constant parameters η_0, c_1, c_2, c_3, were obtained from Hayek et al. 2011 which contains values from sources such as the manufacturer and the Australian and New Zealand Solar Energy Society (ANZSES).

The equation for useful heat gain for a concentrated collector obtained from (ASHRAE, 2019) is defined as follows,

$$\dot{Q}_u = F_R I_{DN}(\tau\alpha)_\theta(\rho I') - F_R U_L(\frac{A_r}{A_a})(T_{fi} - T_a) \tag{11}$$

Where, I_{DN} is the Direct normal irradiation (W/m^2), ρ is the reflectance of the concentrator surface, A_a is the area of aperture, A_r is the area of receiver and I' refers to the fraction of reflected or refracted radiation received by the absorber A variable 'S' which represents the total absorbed radiation per unit aperture area can be introduced into the useful heat gain equation shown above.

$$S = \frac{I_{DN}(\tau\alpha)_\theta(\rho I')}{A_a} \tag{12}$$

The equation above was substituted into the useful heat gain equation to obtain a new expression for useful heat gain as follows.

$$\dot{Q}_u = F_R A_a S - F_R U_L(\frac{A_r}{A_a})(T_{fi} - T_a) \tag{13}$$

The equation for calculation of Collector heat removal factor F_R is the same as the one illustrated in Equation 3. The equation for Collector Efficiency Factor F' of a concentrated collector is defined as follows,

$$F' = \frac{\frac{1}{U_L}}{\frac{1}{U_L} + \frac{D_o}{D_i h_{fi}} + \frac{D_o}{2k} \ln\left(\frac{D_o}{D_i}\right)} \tag{14}$$

Where, D_o is the outer diameter of receiver (m), D_i is the inner diameter of receiver (m) and K id the thermal conductivity of copper (W/m^2 °C). The equation for Collector Flow Factor F'' is defined as follows,

$$F'' = \frac{\dot{m}C_p}{A_r U_L F'}\left[1 - \exp\left(-\frac{A_r U_L F'}{\dot{m}C_p}\right)\right] \tag{15}$$

The total irradiance of the sun was obtained via data available at the Prediction of Worldwide Energy Resource (POWER) which is maintained by the National Aeronautics and Space Administration (NASA). The latitudinal and longitudinal coordinates of Kings Hospital were entered into the website and the monthly average Global Horizontal Irradiance (GHI) values for the year 2021 were obtained. A copy of the results obtained is available in Appendix B of this report. The average irradiance for the for the year was determined to be 5.52 kWh/m^2/day. This value was converted to its equivalent value in W/ m^2 by first multiplying the value by 1000 to get the value in terms of Watts and then dividing the value by the number of sun hours per day, based on the daily GHI values obtained it was observed that an average of 11 sun hours were experienced in Sri Lanka. Note that since both the numerator and denominator are multiplied by 3600 to convert the value to seconds, both terms cancel each other, hence the annual GHI value was determined to be 501.82 kW/m^2. The average annual value of Direct Normal Irradiation (DNI) during the year 2021 was used for the calculation of efficiency of Concentrated collectors. The average value obtained from NASA POWER website was 4.05 kWh/m^2/day, a conversion process similar to that followed for the GHI value conversion was followed and the DNI value was determined to be 368.18 W/m^2 (NASA POWER 2022).

2.2 Manufacturer Specifications of Each Collector Type

Manufacturer specified information regarding the capacity and physical dimensions of solar collectors provided by the three suppliers mentioned earlier were obtained to determine the capacity, physical dimensions and cost of each collector type which will be used for the gross collector area calculation, tank sizing analysis and financial feasibility analysis. Based on information obtained for flat plate collectors from Alpha Thermal Systems the maximum capacity of the flat plate collector available in the market available was 300 litres/ day. This collector has a width of 2030 mm and length 2010 mm with a total of 16 tubes within the said panel. The cost per collector was determined to be 356,250 LKR, which includes the cost of the collector panel only *i.e.*, excluding the cylindrical tank it is provided with. Information regarding evacuated tube collectors obtained from JFA Sunbird revealed that the maximum capacity that could be supplied by one evacuated tube collector unit is 450 litres. The collector has a width of 2400 mm and length 1900 mm with a total of 30 vacuum tubes within the said panel. The cost per collector was determined to be 437,750 LKR, which also includes the cost of the collector panel only. Finally, information obtained from Absolicon revealed that its parabolic trough collector could produce 500 litres of heated water per day. The product which is called Absolicon T160 collector has an aperture area specified by the manufacturer as 5.5 m^2 and uses polymer embedded silver on steel sheet as its reflector material. The manufacturer charges approximately 533 euros per square meter of aperture which converts to approximately 206,500 LKR.

2.3 Heated Water Storage Tank Design Considerations

When considering the design specifications of the heated water storage tank, according to the guidelines published by the American Society of Plumbing Engineers (ASPE) in the year 1980, water storage systems should be able to store between 48.9 to 73.3 litres of liquid per square meter of collector area. However, based on a computer simulation which was run by the University of Wisconsin, the publication states that a value of 61.1 L/m^2 could be considered as an optimum value between the range mentioned earlier (American Society of Plumbing Engineers (ASPE) 1980). The range stated by ASPE was later verified by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in a Handbook published in the year 2012, which stated that a typical liquid system thermal storage should be able to allocate between 40 to 80 Litres of fluid per square meter of collector area (ASHRAE 2012). The formula to determine the tank volume required is given below.

$$\text{Tank volume required} = 61.1 \times \text{Total collector area} \tag{16}$$

Tanks can be constructed in either vertical or horizontal configuration. It should be noted that vertical tanks provide the best performance in terms of stratification of the fluid within the tank, however, if the height available at the location of installation is constrained, horizontal tanks can be used (Kalogirou, 2014). Consideration should also be given to the type of material selected for construction of the storage tank, commonly used construction materials include steel, plastic and concrete (ASHRAE 2012). Materials commonly used for the purpose of heated water storage tank insulation include rigid foam, rigid sheets of polyisocyanurate and fibreglass. The Handbook published by ASHRAE in 2012 provides guidelines regarding the insulation requirements of a storage tank.

$$\frac{1}{R} = \frac{fQ}{A\theta}\frac{1}{(\mathrm{t_{avg}} - \mathrm{t_a})} \tag{17}$$

Where R is the thermal resistivity of the insulation required, f is the specified fraction of stored energy that can be lost in time, Q is the stored energy, A is the exposed surface area of storage unit, θ is the given time period, t_{avg} is the average temperature in storage unit and t_a is the ambient temperature surrounding storage unit. The term $\frac{fQ}{A\theta}$ is referred to as the insulation factor (ASHRAE 2012). The ASHRAE Handbook defines typical insulation factors based on the volume and shape of the storage tank as shown in the figure below.

	Vertical Tank Insulation Factor, W/m^2			
Size, m^3	D to 3D	D/2	D/3	D/4
0.30	6.62	5.93	6.78	6.21
0.45	7.54	6.78	7.76	7.13
0.95	9.68	8.64	7.76	9.09
1.89	12.21	10.91	12.49	11.45
2.84	13.97	12.49	14.29	13.12
3.8	15.36	13.75	15.74	14.42
5.7	17.60	15.74	18.01	16.53
7.6	19.34	17.32	19.81	18.17
11.4	22.18	19.81	22.68	20.82
15.1	24.39	21.83	24.98	22.90
18.9	26.28	23.50	26.90	24.67

Figure 1. Insulation Factor fQ/Aθ for Cylindrical Water Tanks (ASHRAE 2012)

2.4 RETScreen Simulation Setup

RETScreen was used to simulate the costs involved in setting up the solar water heating project and the savings that the hospital can expect to make if they choose to implement the said system. The analysis was carried out by first entering the latitudinal and longitudinal coordinates corresponding to Colombo, Sri Lanka. The base case was then entered into the software. The base case only consisted of a heating system powered only via electricity. The electricity rate in the country which is 28 LKR/kWh, was also entered into the software. The proposed case was also set to use electricity with the same electricity tariff mentioned earlier, the difference between the two cases would be the addition of the solar collectors to reduce the electricity consumption of the base case. Additional characteristics such as the value of manufacturer specified coefficients such as F_RU_L and $F_R\tau\alpha$ were obtained from the built-in solar collector database available in the RETScreen software. miscellaneous losses were entered as 2%, this value generally indicates the losses the collector may incur if there was shading present due to dust on the collector. The software recommends a value between 2 and 5% for well-maintained collectors.

A cash flow diagram of the project was generated for each collector type using the software. A 20-year project life cycle was considered for the cash flow diagram. Parameters such as the annual inflation rate was set to 2.5%, debt interest rate was set to 5%, debt term was set as 5 years, fuel cost escalation rate was set to 3% and the income tax rate which was 14% for health care services was also entered into the software before generating the cash flow diagram. The total cost of the number of solar collectors required and a user designed cost of 0.1% of the total cost was also entered into the software in order to account for the design and assembly cost of the collector setup.

3 RESULTS AND DISCUSSION

3.1 Analysis of the Selected Industrial Application

As mentioned earlier, a hospital was selected as the industrial application to be analysed for this study and inspection of the hospital revealed that it utilized electrically powered geysers to supply its daily hot water requirement. Geysers were installed in all the rooms of the hospital where patients were admitted to. Additionally, geysers were used in departments such as the culinary department, operation theatres and Cath Labs. It was discovered that the hospital consisted of 72 functional patient rooms, therefore considering the additional applications mentioned earlier, the hospital utilized a total of 90 electrically powered geysers to meet its daily hot water requirement. As mentioned earlier, a centralized water heating system was not present, hence the hot water usage could not be measured directly. Therefore, the total monthly water usage of the hospital was obtained over a period of six months as shown in the figure below.

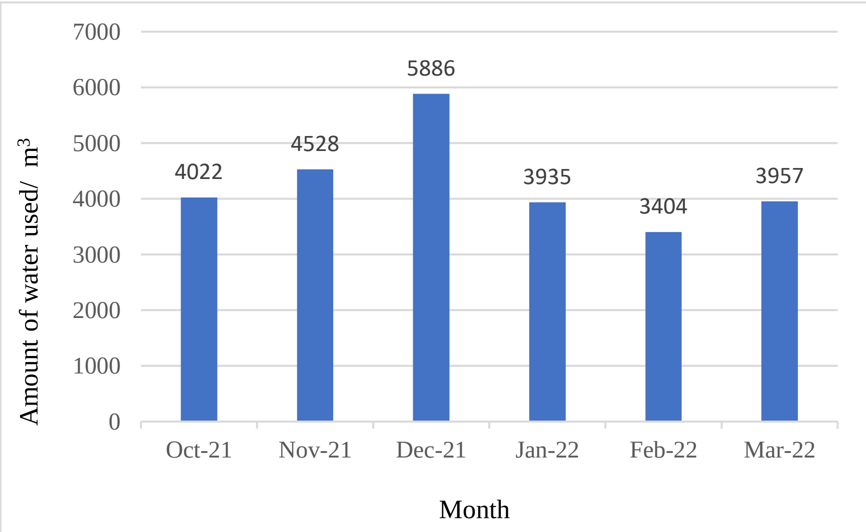

Figure 2. Monthly water consumption of the hospital

An average value for the monthly water usage of the hospital was then obtained as 4289 m^3. Based on the aforementioned applications of hot water, it was assumed that 25% of the total water usage of the hospital accounts for hot water applications. Therefore, the average hot water requirement per month was determined as 1072.25 m^3 which was determined in terms of litres as 35741.7 litres per day. The geyser utilized by the hospital consisted of a 1500W heating element which supplies the heat required to increase the temperature of water. 72 geysers are currently utilized in patient rooms for applications such as bathing, *etc.* it can be assumed that theses geysers are switched on for six hours a day on average. The remaining 18 geysers which are utilized in the kitchen department, operation theatres and Cath lab can be assumed to be switched on for approximately fifteen hours a day on average.

3.2 Efficiencies of Each Solar Collector Type

Based on the theoretical efficiency equations that were derived for each collector type, it was observed that concentrated collectors had the highest efficiency rating (89.9%). Flat plate collectors had the lowest theoretical efficiency (65.8%) whereas evacuated tubes had a more improved efficiency (79.4%) when compared to the performance of a flat plate collector. The reason for concentrating collectors having the best overall efficiency was mainly due to its arrangement, which allows for incident beam radiation to be reflected and focused solely on the fluid carrying pipe. The reason for the comparatively poor performance of the flat plate collector was due to the high convective losses involved during the heating of the fluid in this system. An improvement in efficiency was seen in the case of Evacuated Tube Collectors mainly due to the inclusion of a vacuum in the collector tubes to minimize the aforementioned losses (Duffie and Beckman 2013). Parameters such as the area of collector (Aperture area (A_a) in the case of concentrated collectors), fluid inlet temperature, overall heat loss coefficient of the collector, ambient temperature, heat transfer coefficient of water, thermal conductivity of copper and mass flow rate of water were assumed to have the same value during analysis of each collector type in order to maintain a consistency in the results obtained.

3.3 Solar Collector and Corresponding Storage Tank Requirements

The total number of flat plate collectors required to fulfil the daily hot water requirement of the hospital based on the manufacturer specifications mentioned earlier was determined to be 119 units, the gross area of collectors was then determined to be $485\ \mathrm{m}^2$. A maximum of ten flat plate collectors can be connected in series without producing any significant pressure drop between collectors and without compromising the thermal performance. Attention must also be given to the diameters of restrictor holes in each collector. Restrictor hole diameters at the outlet of each collector should increase from the first collector until it reaches the collector at the middle. The restrictors at the inlet of each collector should decrease gradually starting from the inlet of the collector at the middle of the array (ASHRAE 2012). From Equation 16 it was determined that a tank of volume 29600 Litres would suffice for the flat plate collector system. Using the first diameter and height relationship shown in Figure 1, the length of the tank was determined to be 7.2 m and the diameter was determined to be 2.4m respectively.

The total number of evacuated tube collectors required was determined to be 79 units, the gross area of collectors was then determined to be $360\ \mathrm{m}^2$. In a study conducted by Garg and Chakravertty in 1988, it was discovered that approximately eight evacuated tube collector modules could be connected in series while accounting for a drop in efficiency of about 5%. From Equation 16 it was determined that a tank of volume 22000 Litres would suffice for the evacuated tube collector system. As in the case of the flat plate system, using Figure 1 the tank length and diameter were determined to be 6.3 m and 2.1 m respectively.

The total number of parabolic trough collectors required was determined to be 79 units, the gross area of collectors was then determined to be $428.7\ \mathrm{m}^2$. In the case of the parabolic trough collector, a sharp increase in the pressure drop is observed when relatively high levels of flow rates are utilised, hence the manufacturer suggests setting up three units in series to obtain optimal results. From Equation 16 it was determined that a tank of volume 23800 Litres would suffice for the parabolic trough collector system. Using Figure 1 the tank length and diameter were determined to be 6.48 m and 2.16 m respectively.

According to the insulation factor table shown in Figure 1, the tank volumes in each collector setup is greater than 18.9 m^3, hence a minimum insulation factor of 26.28 is required for each tank. the thermal conductivity of the insulation material computed using Equation 17 was $1.24\ \mathrm{W/mK}$.

3.4 Equity Payback Period of Each System

As mentioned earlier, a financial feasibility analysis was performed using RETScreen. The total price of the collector units and an additional 0.1% of the total cost for each type was considered as the installation cost. The equity payback period for each case was computed based on user defined parameters such as discount rate, inflation rate mentioned earlier. The results of the 20-year project life cycle simulation for each case is shown in the table below.

Table 1. Equity payback period for each collector system

	Flat Plate Collector	**Evacuated Tube Collector**	**Parabolic Trough Collector**
Cost of units / LKR	42,393,750	34,582,250	75,886,570
Equity Payback period / Years	9.0	7.4	12.6

3.5 Sensitivity Analysis of Payback Period for Each System

As mentioned earlier, the equity payback period for the three collector types were generated based on a fuel cost escalation rate of 3%. The effect of varying the fuel cost escalation rate on the equity payback of each system was also analysed using RETScreen simulation software. The fuel cost escalation rate was varied from 0 to 5% to determine the effect it would have on the number of years required to achieve equity payback. The results obtained are shown in the figure below.

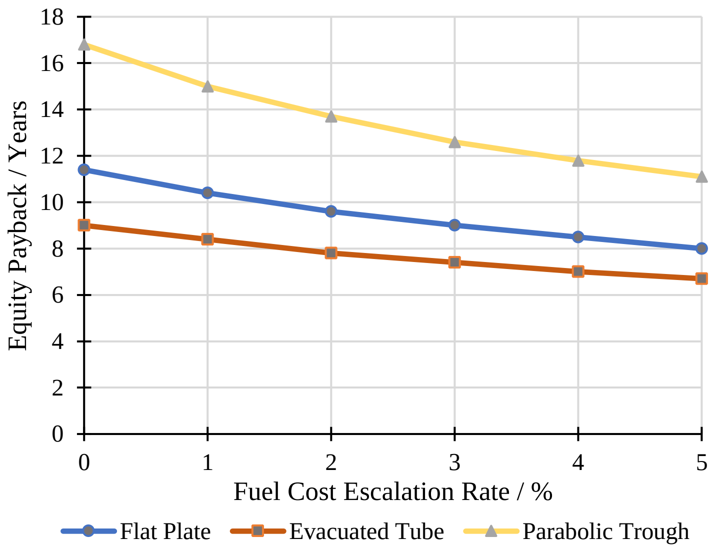

Figure 3. Effect of fuel cost escalation rate on equity payback

Based on the figure above it can be observed that an increase in fuel cost would lead to an exponential decrease in number of years required to achieve equity payback. For the case where there is no increase in fuel cost, the flat plate system would take approximately 11.4 years to achieve equity payback, while the evacuated a system would take approximately 9 years to achieve equity payback and finally the parabolic trough system would take up to 16.8 years to achieve equity payback. For the best-case scenario where the fuel cost would rise at a rate of 5%, the equity payback period of flat plate, evacuated tube and parabolic trough would decrease by 29.8, 25.6 and 33.9% respectively, from the values mentioned for a fuel cost escalation rate of 0%.

3.6 Electricity Consumption Analysis of Each System

The electricity consumption for each case was also obtained using RETScreen as mentioned earlier. The figure below indicates the electricity requirement annually to achieve the required water heating content for the base case, flat plate collector system, evacuated tube system and the parabolic trough system.

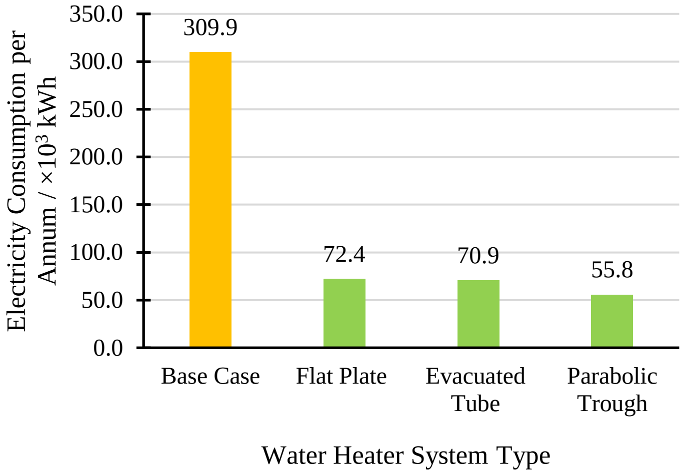

Figure 4. Electricity consumption per annum of each water heating system type

Based on the figure above it can be observed that the base case scenario which involves the use of electricity to obtain the total water heating requirement consume approximately 309,900 kWh of electricity annually. The flat plate system consumes approximately 72,400 kWh of electricity which is a 76.6% reduction in annual consumption, while the evacuated tube system consumes approximately 70,900 kWh which is a 77.1% reduction in annual consumption. Finally, the parabolic trough system consumes the least amount, approximately 55,800 kWh of electricity which is an 82.0% reduction in annual consumption. Note that these values represent electricity consumed solely to heat the required water content, hence actual consumption values may vary depending on the pump work and other electrical components involved.

3.7 Greenhouse Gas Emission Analysis of Each System

RETScreen has a built-in tool that analyses the effect a proposed case would have on the total Greenhouse Gas (GHG) emissions of the project. The software requires the user to enter the generation sources of electricity for the base case defined earlier in the software. As discussed in the introduction of this report, 49% of the total electricity generation in the country was accounted for by coal and oil in the year 2021. While the remaining energy requirement was provided by hydro and non-conventional renewable energy sources. When entering fuel types into the software, coal, hydro and oil were entered as the main constituents. Once the main constituents were entered and their respective fuel mixes, *i.e.*, percentage contribution to the grid, were entered into the software. The software then takes into account parameters such as, CO_2, CH_4 and N_2O emission factors in terms of kg/GJ of each fuel source from its database. In addition to these values the software also determines electricity generation efficiency of each fuel type and determines the total GHG emission factor.

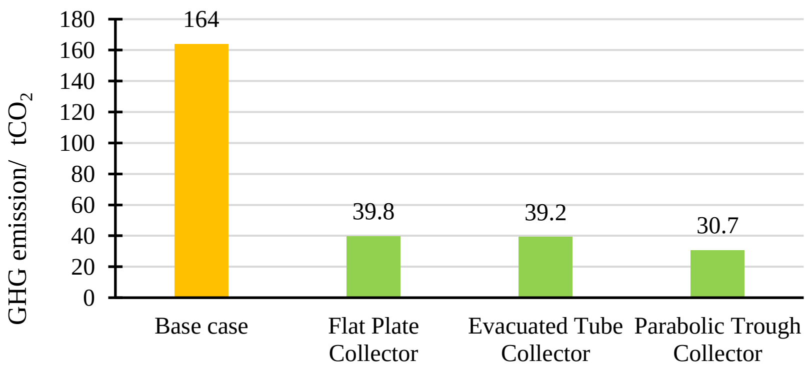

Figure 5. Annual Greenhous Gas emissions of each water heating system type

Based on the figure above it can be observed that the base case scenario which consumed the highest amount of electricity as mentioned earlier produced approximately 164 tonnes of CO_2 equivalent Greenhous Gas. The flat plate system produced approximately 39.8 tonnes of CO_2 equivalent which is a 75.7% reduction in annual emission, while the evacuated tube system produced approximately 39.2 tonnes of CO_2 equivalent which is a 76.1% reduction in annual emission. Finally, the parabolic trough system which produced the least amount due to its very low consumption of electricity, produced approximately 30.7 tonnes of CO_2 equivalent which is an 81.3% reduction in annual consumption.

4 CONCLUSIONS

In this study a suitable non-residential application was selected and the feasibility of implementing a centralised water heating system was analysed. Three types of collectors were considered and evaluated. From the theoretical calculations and simulations, it was concluded that although PTC had the highest efficiency (89.9%), the equity payback was 5.5 years higher than the ETC which had the second highest efficiency (10.5% lesser than PTC), hence the ETC setup would be the most viable option.

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