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Techno-economıc Analysıs of Evacuated Tube Solar Water Heater usıng F-chart Method

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Abstract. Solar thermal utilization, especially the application of solar water heater technology, has developed rapidly in recent decades. Solar water heating systems based on thermal collector alone or connected with photovoltaic called as photovoltaic-thermal (PVT) are practical applications to replace the use of electrical water heaters but weather dependent performance of these systems is not linear. Therefore on the basis of short term or average weather conditions, accurate analysis of performance is quite difficult. The objective of this paper is to show thermal and economic analysis of evacuated tube collector solar water heaters. Analysis done by F-Chart shows that evacuated tube solar water heater achieves fraction value of 1 to fulfil hot water demand of 150liters and above per day for a family without any auxiliary energy usage. Evacuated tube solar water heater show life cycle savings of RM 5200. At water set temperature of 100°C, RM 12000 is achieved and highest life cycle savings of RM 6100 at the environmental temperature of 18°C are achieved. Best thermal and economic performance is obtained which results in reduction of household greenhouse gas emissions, reduction of energy consumption and saves money on energy bills.

1. Introductıon

Hot water is necessity for the basic life activies from domestic to industrial purposes. Basically, fuels used for heating water release huge amount of coarbon dioxide in the environment, which cause the pollution. It has been predicted that there will be a great shortage in the supply of conventional fuels if a suitable alternatives are not found [1, 2]. Therefore, solar energy has been the best option to mitigate the pollution and avoid the threat of depleting resources of energy. Solar water heaters are developed and are being used to heat the water with solar energy all over the world. The SWH system investigated consists of mainly three parts, namely a flat plate solar collector, a heat exchanger (storage tank) and a circulating pump[3]. Solar water heating systems have been the famous application to convert solar radiations as an energy source into thermal energy [4]. Furthermore, these days solar water heating is obtained by combination of thermal collector with photovoltaic (PV) modules called as PVT, which gives two fold benefits. Firstly, it gives improved electrical efficiency of PV module by extracting heat form PV panel which is used for water heating and some other applications. Secondly, size of overall system reduces which occupies lesser area as compared to both thermal collectors and PV panels if installed separately. In today's market, evacuated tube solar water heaters are most cost-effective, efficient and reliable as compared to others types of solar water heaters[5]. There are many types of evacuated tube solar collectors to choose from, making them extremely versatile in the applications they can be used for. These systems are smart in size and efficient in thermal conversion with reasonable prices [6, 7]. Fortunately, Malaysia is blessed with abundant solar energy. In Malaysia, monthly average daily sunshine duration is from 4hrs to 8hrs with monthly average daily solar radiation value of 4000-5000 Whr/m2[8]. Due to the favourable climate conditions in Malaysia, it has a high solar energy potential specially in harnessing solar thermal energy [9]. Three years monthly average data of solar irradiations was collected from Subang/KL meteorological station to analyse solar water heaters in Malaysian climate. Evacuated tube solar water heater is analysed through F-Chart method to investigate the economic and thermal perfoamnce.

1.1 F-Chart Method

F–Chart which is designed by S.A. Klein and W.A Beckman is an authoritative source for design and analysis of solar system. The chart scheme provides means for predicting the thermal behaviour of the dynamic solar heating systems easily (by means of air or liquid as fluid used) and the solar domestic hot water systems [10]. The F–chart scheme is principally a relation of effects from numerous simulations of the solar heating systems. The environments of the resultant relation gives *f*, the part of scheduled heating load delivered by the solar energy as a formula of 2 dimensionless quantities (variables) involving a collector features, heating of loads, and the local climate [11]. The part of monthly heating load (for space heating and hot water) is delivered by the solar energy which is a formula of 2 dimensionless quantities, *A* and *B*. Where the ratio of collector losses to heating loads is *A* and the ratio of absorbed solar radiation to the heating loads is *B* [12].
Reference collector energy

$$X = \frac{Loss\ during\ a\ month}{Total\ heating\ load\ during\ a\ month} \tag{1}$$

$$Y = \frac{Total\ energy\ absorbed}{Total\ heating\ load} \tag{2}$$

The equations (1) and (2) for X and Y can be written as follow:

$$X = F_R . U_L . \frac{F_R'}{F_R} \times \left(T_{ref} - \overline{T_a}\right) \times \Delta\tau \times \frac{A_c}{L} \tag{3}$$

$$Y = F_R(\tau\alpha)_n \times \frac{F_R'}{F_R} \times \frac{(\overline{\tau\alpha})}{(\tau\alpha)_n} \times \overline{H_T}\mathrm{N} \times \frac{A_c}{L} \tag{4}$$

where
Ac = Area of solar collector (m2 or ft2),
F'R = Collector-heat exchanger efficiency factor (%),
FR = Collector heat removal factor (%),
UL = Collector overall energy loss coefficient (W/m2-°C or Btu/hr-ft2-oF),
Δτ = Total number of seconds (SI) or hours (IP) in the month,
T a = Monthly average ambient temperature (°C or °F),
L = Monthly total heating load for space heating and hot water (GJ or MMBtu),
HT = Monthly averaged, daily radiation incident on collector surface per unit area (MJ/m2 or Btu/ft2),
N = Number of days in the month,
(τα) = Monthly average transmittance-absorptance product (%),
(τα)n = Normal transmittance-absorptance product (%), and
Tref = An empirically derived referenc$f$e temperature (100 °C or 212 oF).

The F-Chart equations for the fraction *f* of the monthly space and water heating loads supplied by solar energy are the following.

$$f = 1.04Y - 0.065X - 0.159Y^2 + 0.00187X^2 - 0.0095Y^3 \quad \text{(Air system)} \quad (5)$$

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3 \quad \text{(Liquid system)} \quad (6)$$

The F-Chart equations for the fraction *f* of the monthly space and water heating loads supplied by solar energy are given as equations 5 and 6 respectively.

2. Methodology

Using F-chart software, thermal and economic output of the system has been calculated by putting solar evacuated collectors data and monthly weather data from Subang/Kuala Lumpur meteorological station, active domestic hot water system data and economic data. The input data is shown in Tables 3.1, 3.2, 3.3, 3.4 respectively.

Table 1. Evacuated tube collector data (F-Chart).

Parameters	Units	Evacuated tube
Number of collector panels	-	3
Collector panel area	m^2	2.86
FR×UL (Test slope)	W/m^2-°C	1.652
FR×TAU×ALPHA	-	0.480
Collector slop	Degrees	15
Collector azimuth (South=0)	Degrees	0
Collector flow rate/area	kg/sec-m^2	0.020
Collector fluid specific heat	kJ/kg-°C	4.15

Evacuated tube solar water heating system is taken from RETScreen database, which is Solar Rating and Certification Corporation certified collector commercially used all over the world [13].

Table 2. Weather view/change input data (F-Chart).

Months	Solar Rad. [kJ/m^2]	Temp. [°C]	Humidity [kg/kg]	Mains [°C]	Reflect.	°C-days
Jan	15270	26.1	0.0173	27	0.30	44
Feb	15290	26.5	0.0170	27	0.30	32
Mar	19100	26.8	0.0182	27.1	0.30	34
Apr	17690	27.0	0.0190	27.3	0.30	29
May	21630	27.2	0.0192	27.4	0.30	28
Jun	17930	27.0	0.0187	28.0	0.30	29
Jul	20310	26.6	0.0183	27.2	0.30	36
Aug	18430	26.6	0.0182	27.0	0.30	36
Sep	15940	26.4	0.0183	27.5	0.30	37
Oct	15700	26.3	0.0184	27.1	0.30	41
Nov	19110	26.1	0.0184	27.6	0.30	42
Dec	20140	26.0	0.0187	27.3	0.30	46

Where,
Solar rad are the radiations incident on solar panel in kJ/m^2
Temp is atmospheric temperature in °C.
Humidity is the humidity ratio in kg/kg.
Mains is the temperature of main water supply in °C.

Reflect is the fraction of reflected solar radiations.
°C-days is the degree-days in temperature °C.

Table 3. Active domestic hot water system data input (F-Chart).

Active Domestic Hot water system		
Location	Subang/Kuala Lumpur	
Water volume/collector area	300	Litres/m^2
Fuel	Electricity	
Efficiency of fuel usage	90%	%
Daily hot water usage	150	Liters
Water set temperature	55	°C
Environmental temperature	27	°C

Where,
Water volume/collector is the amount of water volume in single tank system.
Fuel is auxiliary fuel used along with solar energy.
Daily hot water usage is the amount of water used per day.
Water set temperature is the required temperature of the water set by user.
Environmental temperature is the temperature of surrounding air.

Table 4. Economics Parameters inputs (F-Chart).

Parameters input	**Detailed**	**Units**
Cost per unit area	n/a	RM/m^2
Area independent cost	6000	RM
Price of electricity	0.2500	RM/kW-hr
Annual % increase in electricity	1.0	%
Period of economic analysis	20	Years
% Down payment	100	%
Ture % property tax rate	3.0	%
Commercial system?	No	%

Where,
Cost per unit area is the cost of the heating system unit wise but not as a whole price.
Area independent cost is the system's whole cost, if it is given then cost per unit area is not applicable.
Price of electricity is the unit cost of electricity used as auxiliary energy.
Annual % increase in electricity is the expected increase in the unit price of electricity.
Period of economic analysis is the total time period for which the solar water heaters are analysed for their performance.
% downpayment is the partial payment made at the time of purchase of the system with the balance paid later as a term of mortgage.
True % property tax rate is the ratio of the increment in real estate taxes due to the solar system to the cost of the solar system.
Commercial system? Set "Yes" or "No" to indicate if the solar system is on private homes or used as commercial purpose.

3. Results and discussions

F-chart is an analysis tool to design solar water heating systems. Many types of solar system can be analysed and designed for long term average performance. It is carefully constructed correlation which based on simulations with a streamlined version of TRANSYS program. F-chart has been used as verification tool for TRANSYS simulations, experiments and other programs for comparing accuracies. The average availability of solar energy on monthly basis based on last 3 years data from Subang/KL meteorological station is used. From the F-chart calculations solar fraction of value 1.00 is obtained through solar water heater throughout the year. This shows that evacuated tube solar water heater with can fulfil 100% domestic hot water demand of about 150 litres minimum on daily basis.
Figure 1 draws the picture of long run economic benefits (in terms of yearly savings) of shifting to solar energy source. As per this analysis, in 20 years, RM5200 can be saved in the case of evacuated collector solar water heater. While solar fraction is constant as value of 1.0 along the time period of 20 years, which results in total life time saving of amount RM5200 as mentioned earlier. The figure shows the progressive improvement in life cycle savings even after time of 20 years. Hence, it is a significant contribution to overall national as well as personal savings.

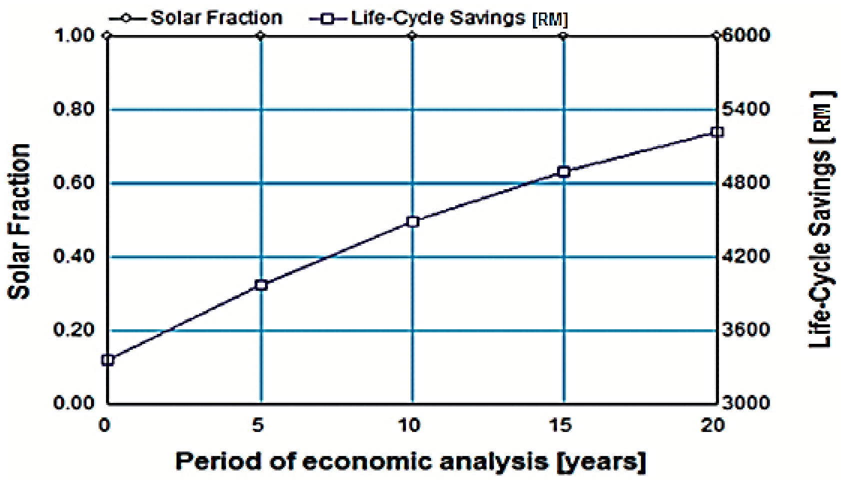

Figure 1. Solar fraction and life cycle savings versus period of economic analysis (years).

Figure 2 shows the association of daily hot water consumption (horizontal axis) with solar fraction and projected life-cycle savings (both scaled vertically). It shows that as water consumption increases, the life-cycle savings also increases, according to this, higher the consumption, higher the savings will be gained. It can, hence, be concluded that large consumers are more to be benefitted from the solar heating system. It is however important to note that the solar fraction falls sharply once the consumption reaches 275 litres a day. This decline in the solar fraction sets in because as demand of hot water increases, it requires more of non-solar more expensive heating sources. With evacuated collector installed, life-cycle savings can go higher than RM 12, 000 even with the increase in hot water usage more than 500 liters. Hence, it shows that evacuated solar water heaters are with more capability and flexible to serve the domestic needs.

The Figure 3 portrays how solar fraction and life-cycle savings behave with change in water set temperature. For evacuated collector solar water heater, the solar option works well at lower temperatures, sufficing the energy requirements and maximizing the savings at the same time. Below 55°C, there appears no need of additional source of heating technology as the solar system suffices. Life-cycle savings also are affected at higher temperatures, due to significant decline in solar fraction. It shows that higher the water set temperature, lesser will be the solar fraction, while life cycle savings tend to increase to certain level. From the results it shows that evacuated collector solar water heaters are more stable and flexible in serving hot water at higher temperatures more than 55°C with the solar

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fraction of 0.70. In terms of life cycle savings, if water set temperature is set at 100°C then RM12000 is achieved by evacuated tube collector solar water heaters.

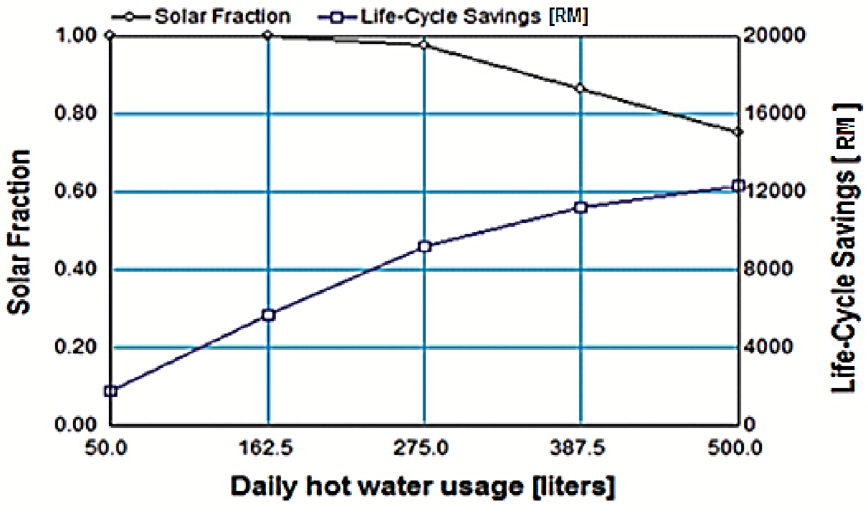

Figure 2. Solar fraction, life cycle savings and daily hot water usage.

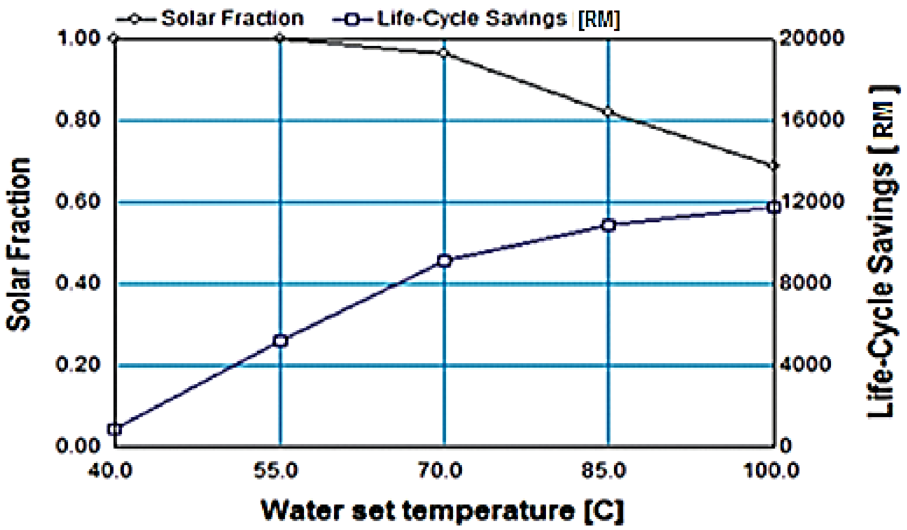

Figure 3. Solar fraction, life cycle savings versus daily water set temperature.

Figure 4 analyses the impact of environmental temperature on solar fraction and life cycle savings. Evacuated collector solar water heaters are highly efficient as they show good performance even at lower environmental temperatures of 18°C. Throughout the temperature scale the solar fraction obtained through these collectors is constant as 1.0. Where, life cycle savings decline because of the reason that cost of solar water heaters is set at RM6000 and the water set temperature at 55°C as input values. Considering these input values, life cycle savings will obviously decrease as the solar water heaters will no longer play major role to heat the water if the environmental temperature goes higher. Evacuated solar water heater results in the highest life cycle savings of RM 6100 at the environmental temperature of 18°C and lowest savings of RM3900 at the temperature of 40°C.

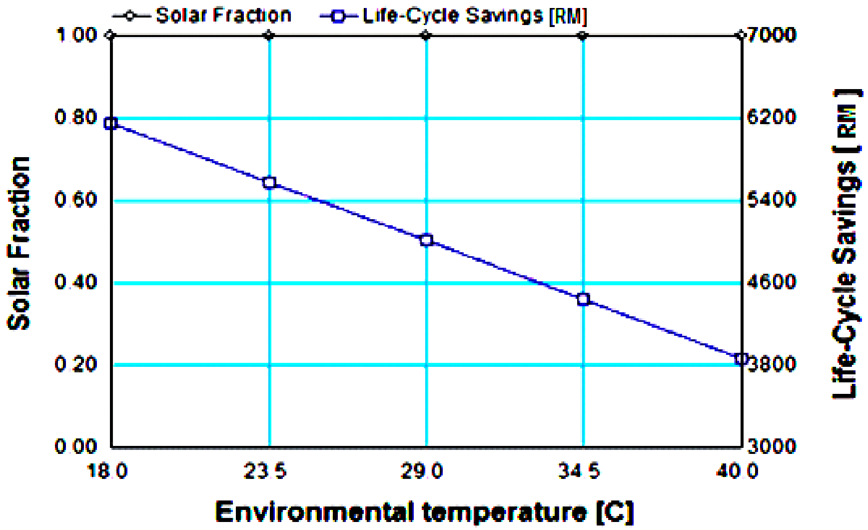

Figure 4. Solar fraction, life cycle savings versus daily environmental temperature.

4. Conclusion

It can be concluded that F-Chart analysis of evacuated tube solar water heater performance shows the best results in the climatic conditions of peninsular Malaysia. As it is obvious from the results that evacuated tube collector solar water heater achieves the best thermal output as it obtains solar fractions of 1.0 with excluding the option of using auxiliary energy. It saves total life time saving of amount RM5200 for the time of 20 years. Hence, it is a significant contribution to overall national as well as personal savings. Overall; evacuated tube solar water heater gives satisfactory performance thermally, economically and environmentally. Evacuated collector solar water heater will serve the needs with maximum thermal output with extra litres of water without any auxiliary electric water heater installation and energy use.

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