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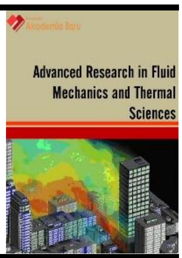

Analysis of Photovoltaic Thermal Using F-Chart Method for Domestic Hot Water

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ABSTRACT

The purpose of this analysis is to determine the feasibility of the photovoltaic-thermal collector for domestic water heating application. Theoretical F-chart method was adopted in estimating the monthly energy generated by the solar water heating system. The study conducted in Ayer Keroh, Malacca where the weather data analysed using isotropic model. The monthly water heating load is designed to meet the requirements of a typical family house with four occupants. The collector tilt angle, heat transfer fluid, transmittance absorptance and loss coefficient follow the design parameters imposed by the F-Chart Method. Detail analysis indicates the photovoltaic thermal system is capable of meeting 94.0% of annual water heating load demand under optimal surface area of 7.48 m². The system produced 2,562.60 kWh heating energy per year, which is almost equivalent to the solar thermal performance under 5.61 m². In conclusion, the integration of photovoltaic thermal is acceptable for domestic water heating application in a tropical climate such as Malaysia although it generates lower thermal energy output per area than the conventional solar thermal collector.

Keywords:
Domestic Solar Water Heating, F-Chart Method, Photovoltaic Thermal Collector and Solar Fraction

1. Introduction

Solar energy is part of sustainable resources besides wind, ocean wave, hydro and geothermal. The technology converts incoming radiation of the sun into useful electric and thermal energy using solar collector. A new design such as the photovoltaic-thermal collector is a combination of the thermal collector and photovoltaic module. It is capable of producing both electricity and heat energy simultaneously. This innovative design is seen as a viable option in future especially for the domestic and industrial water heating application. Reviews from the past four decades found the solar insolation and ambient temperature are two main factors influencing the performance of the photovoltaic thermal system [1].

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At present, more than 50.0% of the harvested solar radiation transformed into heat while less than 20.0% converted into electricity [2]. The high heat generated by the collector is useful for water, space and process heating application. A detailed comparison of various photovoltaic thermal collectors concludes that the average thermal efficiency ranges between 40.0 to 80.0% depending on the design and heat transfer medium [3]. Flat plate, evacuated tube and concentrating collector are three main design studied in the present day. Out of three collectors, the flat plate is the most popular, due to its simple design for optimisation [4].

The long-term review indicates that the water-based photovoltaic thermal system is more promising for future investment [5]. Recent trends show significant interest in the optimisation of the photovoltaic-thermal collector. An investigation by Modjinou *et al.,* [6] confirms the thermal efficiency of the hybrid collector is between 50.7 to 54.7% using both numerical and experimental validation. Different simulation studies conducted by Rosli *et al.,* [7, 8] demonstrate the possibility of optimising the thermal efficiency of the photovoltaic-thermal collector by manipulating the geometry and dimension of the absorber. Another modelling validation by Sachit *et al.,* [9] proves the thermal and electrical efficiency of the hybrid collector with distinct absorber design does correlate with the mass flow rate of working fluid under different solar radiation level. Besides design, the output performance of the collector could be improved significantly by utilising different materials [10]. Variation in the type of solar cell for photovoltaic thermal collector evaluation concludes that crystalline silicon gained the highest total energy, followed by polycrystalline silicon, copper indium gallium selenide, cadmium telluride and thin film amorphous silicon [11]. The heat generated by the collector could be improved further by optimising the configurations of the solar water heating system. An active solar water heating utilising heat exchanger is more effective than conventional passive system [12]. Although more effective, the complexity is still higher than a passive system [13].

The theoretical analysis published by Vokas *et al.,* [14] confirms the capability of the photovoltaic thermal system in meeting domestic heating and cooling demands for a temperate climate. Another interesting discussion examining the output performance of the photovoltaic thermal system under different collector arrangements and mass flux by Yuan *et al.,* [15] is also worth including in the analysis. Although the thermal and electrical efficiency of the photovoltaic-thermal collector extensively investigated, the commercialisation of the technology remains limited in the present day. The objective of this study is to determine the feasibility of the domestic water heating system utilising photovoltaic thermal collector in Malaysia. Evaluation is conducted numerically by employing the F-Chart method. Characteristics and design criteria of the photovoltaic-thermal collector were generated based on relevant parametric case studies. Solar fraction was evaluated in the analysis measures of the thermal efficiency of the water heating system. Feasibility of photovoltaic thermal collector was determined by comparing the amount of energy produced with conventional solar thermal, which operates under similar configuration.

2. Methodology

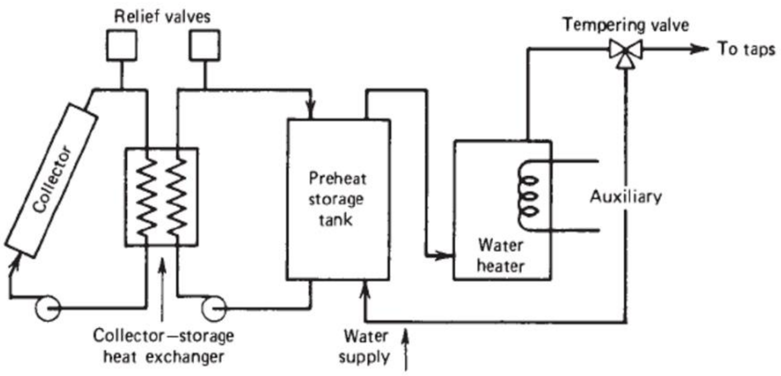
2.1 Initial Configurations

Theoretical evaluation for domestic water heating system is conducted following the number of modules connected in a series arrangement. Two flat plate collector with a single glass cover chosen for analysis. Parameters of photovoltaic-thermal collector derived from the parametric study conducted by Rosli *et al.,* [7] while information for solar thermal is acquired from datasheet provided by the manufacturer [16]. Following Table 1 summarised the parameters of both collectors.

Table 1
Selected Parameters [7, 16]

Parameters	Symbol	Unit	Type of Collector	
			Photovoltaic Thermal	Solar Thermal
Surface Area	A_c	m^2	1.870	1.870
Testing Flow Rate (Water)	$\dot{m}$	kg/s	0.010	0.038
Collector Slope	$F_R U_L$	W/m² °C	5.635	5.287
Collector Intercept	$F_R(\tau\alpha)_n$		0.454	0.632

The domestic solar water heating system is assumed operating under a uniform condition where the thermal loss and other external factors neglected unless stated in the analysis. Correction for parameters in Table 1 is depended on the arrangement of collector and configurations used by the system. Figure 1 illustrates the layout and design limitation of solar water heating system using F-Chart method [17, 18].



F-Chart Design Parameter For Liquid And Air System

$$0.6 \le (\tau\alpha)_n \le 0.9$$
$$5 \le F_R' A_c \le 120\text{m}^2$$
$$2.1 \le U_L \le 8.3 \text{ W/m}^2\ ^\circ\text{C}$$
$$30 \le \beta \le 90^\circ$$
$$83 \le (UA)_h \le 667 \text{ W/}^\circ\text{C}$$

Fig. 1. Layout and design parameters of solar water heater for liquid system [17, 18]

In Figure 1, the energy evaluation was performed according to the number of collectors employed by the system. The collector is positioned facing south towards the equator at a fixed inclination angle. Pumps, storage tank, tilt angle and heat exchanger parameters were derived from relevant case studies [17- 21]. Table 2 summarised the input data used in the calculation.

Table 2
Water Heating System Parameters [17- 21]

Parameters	Symbol	Unit	Value
Tilt Angle	β	degree	30.0
Flow Rate (Collector Pump)	$\dot{m}_C$	Kg/s	0.122
Flow Rate (Water Pump)	$\dot{m}_P$	kg/s	0.085
Storage Tank Capacity	V	m³	0.250
Water Supply Temperature	T_w	°C	22.5

2.2 Correction Factor and Arrangement of Collector

Correction on collector parameters is required since the flow rate in Table 1 and 2 are varied. In the analysis, the system used identical modules which connected in a series arrangement. The approach suggested by Oonk *et al.,* [22] with extended elaboration by Dubey and Tiwari [23] was applied in the analysis. Following Eq. (1) summarised the formula used in evaluating the corrected ratio between collector and system.

$$r = \frac{\frac{\dot{m}C_p}{A_cF'U_L}\left[1-exp\left(\frac{-A_cF'U_L}{\dot{m}C_p}\right)\right]\Big|_{use}}{\frac{\dot{m}C_p}{A_cF'U_L}\left[1-exp\left(\frac{-A_cF'U_L}{\dot{m}C_p}\right)\right]\Big|_{test}} \tag{1}$$

In Eq. (1), the $F'U_L$ calculated based on the following equation

$$F'U_L = \frac{-\dot{m}C_p}{A_c} ln\left(1 - \frac{F_RU_LA_c}{\dot{m}C_p}\right) \tag{2}$$

Information required in Eq. (1) and (2) follows the actual testing result of the selected collector with flow rate chosen for the system. Corrected parameters of the collector are evaluated using Eq. (3) and (4), as shown below.

$$F_RU_L|_{use} = rF_RU_L|_{test} \tag{3}$$

$$F_R(\tau\alpha)_n|_{use} = rF_R(\tau\alpha)_n|_{test} \tag{4}$$

Eq. (3) and (4) represent the corrected collector parameters which only valid for single module operation. In this study, the modules are connected in a series arrangement. Hence, corrected formulas according to the number of modules were introduced. The next equations finalised the corrected collector parameter for the system.

$$F_RU_L|_{system} = F_RU_L|_{use}\left(\frac{1-(1-K)^N}{NK}\right) \tag{5}$$

$$F_R(\tau\alpha)_n|_{system} = F_R(\tau\alpha)_n|_{use}\left(\frac{1-(1-K)^N}{NK}\right) \tag{6}$$

In Eq. (5) and (6), the *N* is the number of modules employed by the water heating system which connected in a series arrangement. The *K* parameter is evaluated as follows.

$$K = \frac{A_cF_RU_L}{\dot{m}C_p} \tag{7}$$

Parameters required in Eq. (7) follow the input configurations used by the system. Limitation on the number of collectors employed by the system is fixed up to four modules. A similar approach was repeated for the solar thermal collector.

2.3 Evaluation Method

The evaluation of the domestic system using F-Chart method was conducted based on the theoretical approach suggested by Vokas *et al.,* [14], Klein *et al.,* [17] and Rosli *et al.,* [18]. The annual solar fraction of the solar water system represents the ratio between total energy produced by the system with water heating load required annually, summarised by the equation below.

$$F_{annual} = \frac{\sum(f \times L_h)}{\sum L_h}\Bigg|_{monthly} \tag{8}$$

In Eq. (8), F_{annual} is the annual solar fraction evaluated by dividing the overall monthly energy produced by the system with L_h or the total location monthly water heating load. The solar fraction for a fluid-based system or f was evaluated as follows.

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3 \; where: 0 < X < 18 \; and \; 0 < Y < 3 \tag{9}$$

The value of X and Y in Eq. (9) are denoted as a dimensionless number ratio of the system. X represents the collector losses to heating load ratio while Y represents absorbed solar radiation to heating load ratio. Evaluation of both unknown is performed using the following formulas.

$$X = \left(\frac{A_c}{L_h}\right) F_R U_L \left(\frac{F_R'}{F_R}\right) \left(T_{ref} - T_a\right) \Delta t \; k_1 \tag{10}$$

$$Y = \left(\frac{A_c}{L_h}\right) F_R (\tau\alpha)_n \left(\frac{F_R'}{F_R}\right) \left(\frac{\tau\alpha}{(\tau\alpha)_n}\right) H_T \tag{11}$$

In Eq. (10), demand for T_{ref} or hot water temperature with ambient temperature, T_a follows the operating condition of the system. The monthly operating duration, Δt is measured in second while k_1 is the storage tank correcting coefficient. In Eq. (11), the H_T represent the monthly tilt angle radiation received by the area. Finally, L_h is accounted for monthly water heating load while (F'_R/F_R) represent the collector-heat exchanger efficiency factor for the system. Ranges for (F'_R/F_R) is estimated by following equation.

$$\left(\frac{F_R'}{F_R}\right) = \left[1 + \left(\frac{A_c F_R U_L}{(\dot{m}C_P)_{collector}}\right)\left(\frac{(\dot{m}C_P)_{collector}}{\varepsilon(\dot{m}C_P)_{min}} - 1\right)\right]^{-1} where: 0 < \left(\frac{F_R'}{F_R}\right) < 1 \tag{12}$$

The corrected (F'_R/F_R) of the system depends on the configuration as shown in Table 2. The storage tank correcting coefficient k_1 was calculated as follows.

$$k_1 = \left(\frac{v}{75}\right)^{-0.25} \tag{13}$$

In Malaysia, study conducted by Zahedi *et al.,* [24] and Daghigh *et al.,* [25] shown the effective capacitance factor,v of solar thermal collector evaluated at 75 litre/m² while photovoltaic thermal collector range between 50 to 75 litre/m². However, the value of k_1 varies depending on the volume of water tank chosen for the system. Finally, the transmittance-absorbent ratio for flat-plate collector estimated at 0.97 for 30 degree inclination angle based on graph provided by Klein [26].

2.4 Case Study Location

The city of Ayer Keroh, Malacca selected as a case study location. Previous weather data recorded in 2016 used as reference in this study. The T_a or ambient temperature and daily global radiation, H_G obtained from a nearby weather station located at Fakulti Kejuruteraan Elektrik of Universiti Teknikal Malaysia Melaka (UTeM). An approach developed by Tian *et al.,* [27] is applied in estimating the average tilt angle radiation of location. It is based on the theoretical Liu and Jordan Isotropic Sky model formula [28], shown as follows.

$$\bar{H}_T = \bar{H}_B \bar{R}_B + \bar{H}_D \left(\frac{1+\cos\beta}{2}\right) + \bar{H}_G \rho_g \left(\frac{1-\cos\beta}{2}\right) \tag{14}$$

In Eq. (14), $\overline{H}_B$ is the average beam while $\overline{H}_D$ is the average diffuse and $\overline{H}_G$ is the average global radiation of location. The tilt angle, β is determined by measuring the degree of inclination between the ground bases with a collector surface plane. The surface albedo or ρ_g is estimated according to the surface condition of the surrounding area as studied by Kotak *et al.,* [29] and Taloub *et al.,* [30]. Required diffuse radiation component estimated using an Artificial Neural Network Model equation suggested by Azhari *et al.,* [31], shown below.

$$\frac{H_D}{H_G} = 0.9505 + 0.91634K_T - 4.851{K_T}^2 + 3.2353{K_T}^3 \quad (15)$$

In Eq. (15), H_D is the daily diffuse radiations while the location clearness index, K_T is evaluated by the following formula.

$$K_t = \frac{H_G}{H_o} \quad (16)$$

Daily extra-terrestrial radiation in Eq. (16) or H_o is estimated according to the coordinates of the weather station, summarised as follows.

$$H_o = \frac{24 \times 3600}{\pi} G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right) \times \left[\cos\phi\cos\delta\ \sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right] \quad (17)$$

The G_{sc} in Eq. (17) represents the solar constant which is 1367 W/m^2 while *n* is the number of days of the year. The sunset hour angle or ω_s is measured in degree unit and evaluated using Eq. (18).

$$\omega_s = \cos^{-1}(-\tan\phi\ \tan\delta) \quad (18)$$

In Eq. (17) and (18), the latitude coordinates for the weather station or ϕ is situated 2.2744 north while δ is the angle of declination, calculated as follows.

$$\delta = 23.45\ \sin\left[\frac{360(284+n)}{365}\right] \quad (19)$$

In Eq. (19), *n* represent the number of days in each month. After solving the diffuse radiation components, the daily beam radiation or H_B is calculated using the following equation.

$$H_B = H_G - H_D \quad (20)$$

Finally, the $\bar{R}_B$ in Eq. (14) is the average ratio of beam radiation defined according to location parameters summarised as follows.

$$\bar{R}_B = \frac{\cos(\phi-\beta) - \cos\delta\sin\omega'_s + \left(\frac{\pi}{180}\right)\omega'_s\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + \left(\frac{\pi}{180}\right)\omega_s\sin(\phi)\sin\delta} \quad (21)$$

In Eq. (21), π is mathematical constant evaluated at 3.142 while ϕ is the latitude coordinates of weather station which located 2.2744 north. The angle of declination or δ is evaluated using Eq. (19) as mention earlier. The minimum sunset hour angle for the month or ω'_s is identified using the following formula.

$$\omega'_s = min[\cos^{-1}(-\tan\phi\tan\delta) \text{ or } \cos^{-1}(-\tan(\phi-\beta)\tan\delta)] \quad (22)$$

Evaluated tilt angle radiation of location then used to determine the solar fraction of the solar water heater using the F-Chart method.

2.5 Water Heating Load

The system heating load was influenced by factors such as location, water consumption, the number of occupants and hot water temperature. In Malacca, the average water consumption was evaluated at 234 litres per day based on statistics released by Malaysian National Water Service Commissions [20]. The monthly heating load of the system was calculated using the equation below.

$$L_h = nN_P V(T_{ref} - T_{water})\rho C_P \quad (23)$$

The total water heating load or L_h is depended on the number of occupancies, N_P and the daily water consumption per person denoted as V in Eq. (23). An investigation conducted in Malaysia concludes that the water temperature range between 22.0 °C to 25.0 °C under high humidity environment [21]. Hence, the base temperature for incoming water supply or T_{water} was assumed constant at 22.5°C. Finally, preferred hot water reference temperature or T_{ref} is set at 50°C which follows the health and safety standards provided by regulatory bodies [32-35].

3. Results and Discussion
3.1 Corrected Parameters of Collector

Total monthly solar fraction of Ayer Keroh is determined based on configurations of the solar water heating system. The first result presents the corrected parameters for both photovoltaic-thermal and solar thermal collector. Evaluated parameters are depended on the number of modules employed by the system. Following Figure 2 and 3 summarised the result for both collectors.

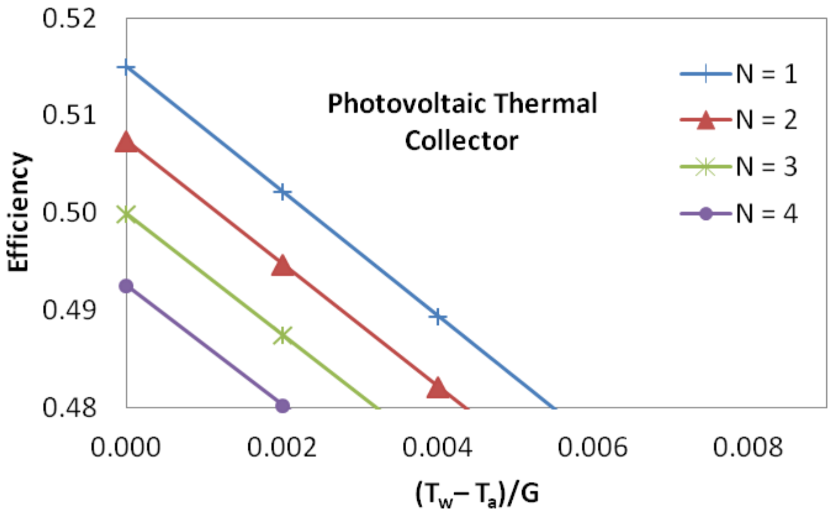


Fig. 2. Corrected Characteristics for Photovoltaic Thermal Collector Based on Number of Modules at Constant Flow Rate ($\dot{m}$ = 0.122 kg/s)

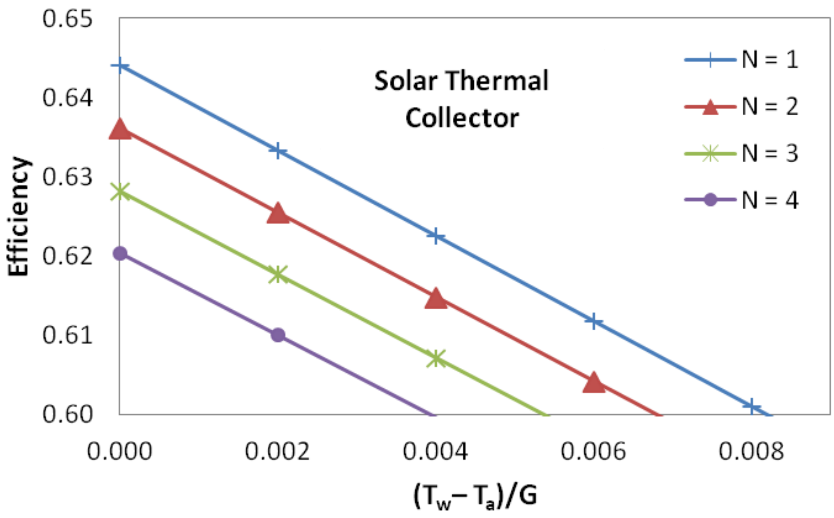


Fig. 3. Corrected Characteristics for Solar Thermal Collector Based on Number of Modules at Constant Flow Rate ($\dot{m}$ = 0.122 kg/s)

Based on observation, the corrected characteristics of collectors in Figure 2 and 3 reduce as more modules added to the system. Increase in the number of modules extends the surface area of the collector. Large exposed areas raise the inner working fluid temperature by consequently lowering the heat loss from collector to surrounding [36]. The low heat loss caused a reduction in the efficiency of collectors.

3.2 Input Parameters of System

The tilt angle radiation, monthly water heating load and ambient temperature of the location are three input parameters required in evaluating the energy generated by the solar water heating system. Calculated parameters are according to location weather data and water consumption pattern. Result in Table 3 summarised the three input parameters for Ayer Keroh.

Table 3
Input Parameters of Solar Water Heating System

Month	Input Parameters		
	Tilt Angle Radiation, H_T (kWh/m²)	Ambient Temperature, T_a (°C)	Heating Load, L_h (GJ)
January	181.45	27.78	0.83
February	164.47	27.45	0.75
March	178.11	28.87	0.83
April	143.79	29.46	0.81
May	127.45	29.18	0.83
June	113.68	28.26	0.81
July	127.75	28.03	0.83
August	137.40	28.35	0.83
September	145.44	28.06	0.81
October	146.30	27.75	0.83
November	125.49	26.78	0.81
December	145.96	26.72	0.83

3.3 Monthly Solar Fraction of System

Monthly solar fraction of Ayer Keroh is determined according to the corrected collector characteristic and input parameter of the system. Data in Table 3 supported by Figure 2 and 3 were evaluated using F-Chart method. The following results summarised the outcome for both collectors.

Result in Figure 4 and 5 indicates the monthly solar fraction of both collectors improved as the more modules added into the solar water heating system. It follows the series connection mode where an increase in the number of collectors improves the fluid output temperature [36]. In a series arrangement, the outlet fluid from the first module connected with the inlet of the second and so on. Accumulation of energy occurred as the heat gained from the first module transferred to the next module. This further increase the thermal energy added to the working fluid. As a result, the outlet fluid temperature at each end of the module rose significantly. High temperature further improves the thermal efficiency thus increase the solar fraction of the water heating system.

Second observation indicates high solar fraction occurred in January to March however varied from April to December. This pattern repeated for every number of modules as shown in Figure 4 and 5. Significant reduction in the monthly solar fraction is due to the variation in solar radiation received by the location. In Table 3, evaluated results derived from weather data indicates the lowest solar insolation recorded in June and highest in January. These findings supported the conclusion provided by Das *et al.,* [1] where solar insolation is one of the main factors influencing the performance of the photovoltaic thermal system. Variation in monthly solar radiation further affects the energy harvested by the collector thus impacts the performance of the system.

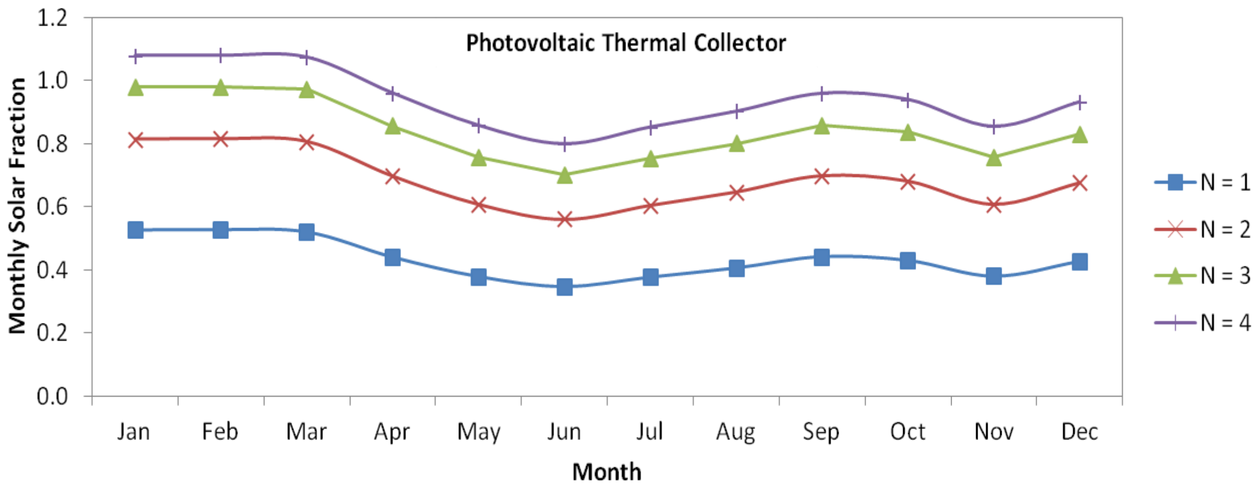


Fig. 4. Result of Photovoltaic Thermal Water Heating System Based on Number of Modules at Constant Flow Rate ($\dot{m}$ = 0.122 kg/s)

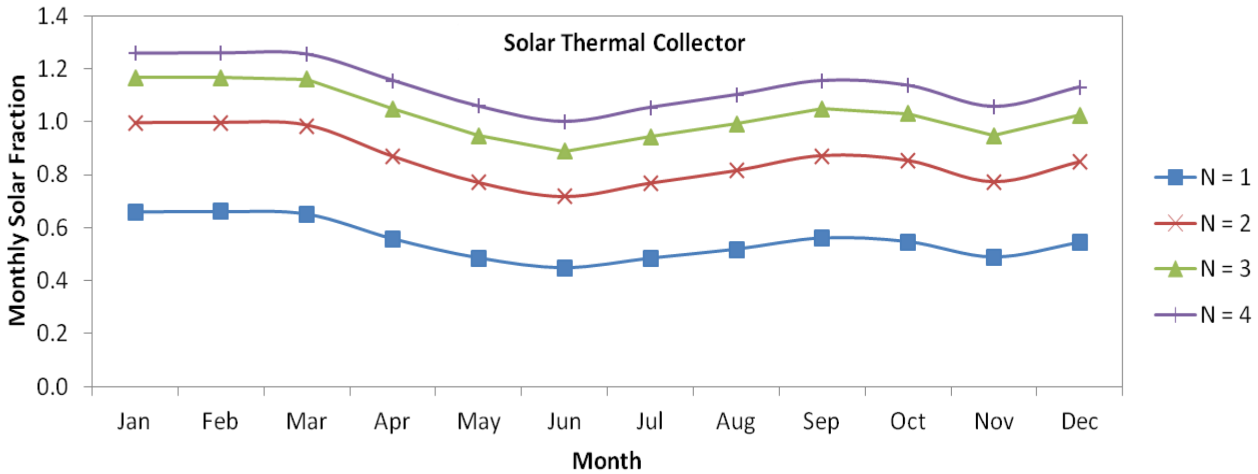


Fig. 5. Result of Solar Thermal Water Heating System Based on Number of Modules at Constant Flow Rate ($\dot{m}$ = 0.122 kg/s)

3.4 Feasibility Analysis

The result shown in Figure 4 and 5 were examined to determine the feasibility of the photovoltaic-thermal collector. Annual energy generated was compared with solar thermal collector under the various numbers of modules. Comparative result is displayed as follows.

Examination in Figure 6 shows the energy produced by solar thermal relatively higher than the photovoltaic thermal collector. Analysis for single module found the solar thermal produce 27.2% more energy under similar surface area. However, the variation reduces to 25.1% as the number of modules increased to two. Under three and four modules, the energy variation further drops to 22.8% and 20.9% respectively. Existed variation is associated with the characteristics of collector. Observation in Figure 2 and 3 found the corrected efficiency of photovoltaic thermal significantly lower than the solar thermal collector. The differences further influence the amount of energy harvested thus explained the result shown in Figure 6. In summary, four modules of the photovoltaic-thermal collector are capable of covering 94.0 % of annual water heating load demand for a house with four occupants. Hence, the feasibility of photovoltaic thermal collector in Malaysia is acceptable for domestic water heating application.

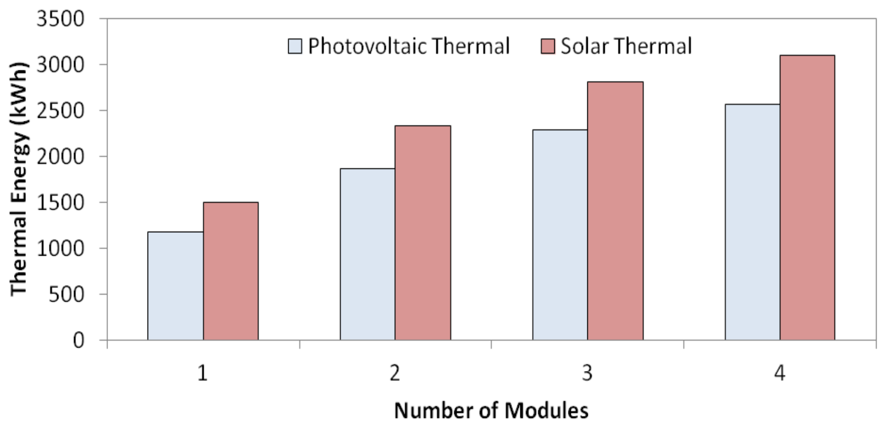


Fig. 6. Comparative Result of Thermal Heating Energy Generated by System Based on Number of Modules at Constant Flow Rate ($\dot{m}$ = 0.122 kg/s)

4. Conclusions

An analytical approach using F-Chart method concludes the harvested thermal energy is capable of covering the demand of a typical family house with four occupants in a tropical climate such as Malaysia. Integration of the photovoltaic-thermal collector with an area ranging from 1.89 to 7.48 m^2 is able to fulfil 43.3 to 94.0% of annual energy demand for domestic water heating application. However, an identical system employing solar thermal collector only requires 5.61 m^2 to meet the annual water heating demand, which is more effective and efficient. From an economic perspective, energy saving per area generated by a photovoltaic thermal collector is less effective than a conventional solar thermal collector. In summary, the photovoltaic thermal collector has great potential in reducing the domestic energy consumption, especially for water heating application. Its hybrid features generating both electric and thermal energy simultaneously applicable of meeting household energy demand. However, operating the hybrid design for heating application alone seems impractical due to the low area to energy ratio of the photovoltaic-thermal collector.

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