Two side serpentine flow based photovoltaic-thermal-phase change materials (PVT-PCM) system: Energy, exergy and economic analysis

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Abstract
Amalgamation of thermal collector at the back of PV overcomes with low energy conversion efficiency issue upto some extent and improves overall efficiency of the systems. Use of phase change materials (PCM) in PV/T collectors as an intermediate thermal storage media offers a promising solution to this problem by storing large amount of heat. The aim of this research work was to design and develop a photovoltaic/thermal-phase change materials (PV/T-PCM) system and evaluate its energy, exergy and economic performance. Lauric acid as PCM contained in leak-proof aluminum foil packets are placed around the flow channel allowing extended period of thermal storage. The PV/T-PCM system has been studied at different volume flow rates viz. 0.5 to 4 L per minutes (LPM) to get the optimized performance of the system. Maximum thermal efficiency of PV/T-PCM collector was found to be 87.72% at 2 LPM. Maximum electrical efficiency of PV and PV/T-PCM systems has been found to be 9.88% and 11.08% (4LPM) respectively. The maximum exergy efficiency of PV and PV/T-PCM system has been found 7.09% and 12.19% (0.5 LPM) respectively. An economic analysis of the proposed system has also been carried out with a view to examine the feasibility of its commercialization.

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1. Introduction

Two or more energy conversion devices or fuels can be combined to get the enhanced efficiency which is typically known as hybrid power systems [1,2]. Increase in photovoltaic (PV) module temperature deceases the electrical efficiency therefore, cooling of PV module may increase the electrical efficiency. Cooling of PV can be done either using air or water as a cooling fluid which is commonly known as photovoltaic/thermal (PV/T) collector which produces electrical and thermal energy simultaneously [3]. The higher overall energy performance is important for the success of PV/T system however, one of the advantage of the PV/T system is production of electrical and thermal energy by the same system which reduce the demands on physical space and equipment cost as compared to the separate PV and solar thermal systems which are placed side-by-side [4,5]. So far, many studies has been conducted by different authors around the World on PV/T to improve the overall efficiency. A comparative study was performed on between hybrid PV/T with active solar heating and cooling systems and passive convectional system, overall thermal and electrical efficiency was found to be enhanced by nearly 25% in the proposed model [6]. Hybrid PV/T collector was also studied using simulation model and it was found that electrical and thermal energies varied between −2.64% to +1.73% and −4.90% to +7.37% with experimental data. This can be considered as a reliable tool both for short-term and long-term yield analysis [7].

There are several technologies, which can advantageously be applied to harness and harvest more thermal energy from the PV/T collector, such as, nanomaterials, phase change materials (PCM), etc. Out of which, the methods of latent heat energy storage is by using PCMs wherein the material can store energy at a particular temperature by changing its phase. Enormous amount of work on

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the PCMs is being carried out around the world to fulfill the demand on usage of solar energy through more efficiently effective methods and systems [8,9]. The PCM study was initiated in 1940 by Telkes and Raymond and research works on the holistic entity were vigorously pursued further up to a certain turning, most probably due to the acute lack of the associated sophisticated equipment of the period until it was significantly needed due to the critical energy crisis in the late 1970s and early 1980s, and since then researches on the PCMs have gained much interest, especially, in the solar energy applications, such as, solar heating [10–12]. During this period many studies had been carried out by the researchers recorded in the form of books and research papers to galvanize further interests [13–16].

The exergy analysis can also be applied on the PV/T module with the phase change material (PCM) in the hybrid (PV/T-PCM) system to evaluate both the energy and the exergy performances [17]. carried out a research on a cascaded thermal energy storage and a signal stage thermal energy storage system and they found that the energy utilization efficiency was higher than the traditional signal stage thermal energy storage system as confirmed by other authors as well [17–19]. Later on [20] investigated and compared those systems and the results showed that the cascaded thermal energy storage not only gave a higher energy efficiency (up to 30%) but also achieved the exergy efficiency (up to 23%) more than the signal stage thermal energy storage system [20] [21]. utilized water as a PCM where he made a bifacial PV module to accordingly source the thermal output in the absence of solar radiation is one of the major mal energy conductivity and special heat energy which have been added a Teflon film as a second glazing front into the PV panel from which the results showed that the overall performance was increased by 5.6% at 50 °C [25] [26], utilized polycarbonate honeycombs to improve a heat transfer in solar collectors [26]. Metal foams (2009–2012) reviewed results showed high thermal conductivities and large specific surface area which were confirmed by many researchers to have the abilities to significantly enhance a heat transfer in phase change materials (PCMs). However, as far as the authors are aware of, metal foams have not so far been examined nor experimented for their potential capability to enhance heat transfer in recuperating tubes [27–30].

The PCMs with a suitable adjustable temperature was chosen in the application because they have high idle heat energy, high thermal energy conductivity and special heat energy which have been found to be very suitable for a solar water heater (SWH) application and building sectors [31,32]. The qualities supplied by the manufacturer may change [33,34]. Hence, in the pre-design stage of the PCM, it is suggested to use the right thermophysical properties of the PCMs which are for the most part described by calorimetric examinations, like Differential Scanning Calorimeter (DSC), and Differential Thermal Analysis (DTA) [35,36]. Generally, a few relevant items can be connected to the machine to gauge the relevant heat properties [37]. Paraffin wax is the most suitable alternative because of its accessibility, non-destructiveness, good liquefying temperatures, and a minimal operating effort [35,36], hence the paraffin wax PCM (Sigma-Aldrich item no. 327212 [39]) was chosen for this test. The liquefying temperature, enthalpy, and specified heat energy were measured by a DSC instrument (Perkin Elmer Pyris calorimeter DSC4000). The DSC was kept running from 30 °C to 85 °C at 5 °C/min heating rate. The DSC test will be illustrating the heating and cooling cycles of the PCM. In the DSC test results, the dissolving temperature of the PCM was measured from the related onset temperature of the heating curve. In this exploratory study, the dissolving temperature was found to be 56.06 °C [40].

It can be seen that none of the above authors done the energy, exergy and economic analysis of two side serpentine flow based PVT-PCM system. The innovative configuration of the shapes and arrangement of pipes are very important in a collector, in the sense that the pipe should be properly heated for better thermal energy output. Thus, if the design is more effective, the output thermal energy will increase. The parallel 2-side serpentine flow absorber collector and a modified pipe arrangement were used throughout the plate collector in this study. The nonuse of PV/T collector for thermal output in the absence of solar radiation is one of the major
drawback of the PV/T collector. Therefore, in the present study PCM has been incorporated in parallel 2-side serpentine flow based PV/T collector to improve the overall performance of the system also to make the system more reliable. The designed and developed PV/T-PCM was evaluated using energy and exergy analysis. With a view to examine the feasibility of its commercialization, an economic analysis of the proposed system has also been carried out. The maximum efficiency was found to be improved and maximum thermal efficiency of PV/T-PCM collector was found to be 87.72% at 2 LPM. Maximum electrical efficiency of PV and PV/T-PCM systems has been found to be 9.88% and 11.08% (4LPM) respectively.

2. Experimental setup

2.1. Design of PV/T system

The detailed design of a thermal collector is as shown in Fig. 1. A 7.62 cm—10.16 cm air gap has been kept between each pipe and a 17.78 cm gap between the parallel two sides of the absorber. The inner side air gap is important as when the sunlight strikes the PV module glass plate, the internal air is heated like the inside of a greenhouse. Nevertheless, water flowing inside the copper pipe takes time due to frictional pressure drop to reach the outlet and during this time, water flowing inside the absorber tubes is heated because of the hot water from the collector outlet.

2.2. PCM thermal control

In the present research, five different PCM materials are tested with DSC, from which lauric acid is selected based on experimental requirement. Table 1 shows the melting temperature range of the five PCMs. Their respective DSC test results are given in Table 1 as well.

2.3. Design of PCM blocks

Phase change materials (PCM) include the use of lauric acid which is a powder like compound at room temperature. There are several techniques used to let the PCM to manage its thermal transfer, e.g., in glass container, in pouch, in separate metal box, etc. However, in the present research, aluminum foil packets have been used in the PCM that is not only light in weight, but it also performs efficient heat transfer. Each packet was 38.5 inches in length and 8 inches in breadth; hence, eight such packets were required to cover the 39 in. x 65.5 in. PV module rear surface. The PCM containing aluminum packets are placed in close thermal contact with the copper flow channel and secured to the PV frame by means of another aluminum sheet. Fig. 2 show the detailed arrangement of the PCM packets on the PV panel rear side.

2.4. Fabrication of PV/T-PCM system

The PV/T collector comprises of two basic components, viz., a PV as an electrical component and a thermal collector as a heat exchanger. The PV module selected for the fabrication of the PV/T unit is a 250-W 60-cell p-Si module. The detailed specification of the module is given in Table 2.

Copper pipes are used because of their high thermal conductivity. The dimensions of the pipes are 1.27 cm in diameter, 1 mm thick and 1475.74 cm long. The copper pipe is attached to an

![Fig. 1. PV module and layout of PV/T thermal collector.](image1)

![Fig. 2. 3D view of flow channel and PCM packets.](image2)

### Table 1

<table>
<thead>
<tr>
<th>Name of PCM</th>
<th>Melting temperature range (°C)</th>
<th>Actual temperature range (°C)</th>
<th>Heat of fusion (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>On set</td>
<td>Peak</td>
<td>End set</td>
</tr>
<tr>
<td>Paraffin</td>
<td>52–54</td>
<td>44.70</td>
<td>52.06</td>
</tr>
<tr>
<td>1-tetradecanol</td>
<td>36–40</td>
<td>36.39</td>
<td>38.23</td>
</tr>
<tr>
<td>Lauric acid</td>
<td>44–46</td>
<td>42.84</td>
<td>43.72</td>
</tr>
<tr>
<td>Decanoic acid synthesis</td>
<td>27–32</td>
<td>30.65</td>
<td>33.01</td>
</tr>
<tr>
<td>Decanoic acid natural</td>
<td>29–33</td>
<td>30.24</td>
<td>32.06</td>
</tr>
</tbody>
</table>

*The electrical characteristics are within 0–3% of the indicated values under Standard Test Conditions. (1000 W/m², 25 °C, AM 1.5).*

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aluminum absorber sheet by means of a thermal conductive paste. The specifications of the conductive paste are as shown in Table 3.

The PCM packet which is made of aluminum sheet of 0.5 mm thick. The PCM packet is coated with a high thermal conductivity non-sticky paper. Hence, each dimension of the packet is 1.27 cm in thickness, 21.59 cm width, and 83.82 cm long. This is a unique idea to use PCM at the rear side of the PV panel. The complete assembly of the PV/T-PCM system is as shown in Error! Reference source not found.3.

2.5. Installation and instrumentation of the experimental set-up

After the design and fabrication stages have been completed, the sub-systems, i.e., PV/T and PCM systems are assembled together to form the complete PV/T-PCM module system and installed in the UMPEDAC Solar Garden at Level-3, Wisma R&D, University of Malaya. The slope of the PV/T panel (\(\beta\)) is determined by Cooper’s equation[42,43]. The slope of the collector is calculated from the equation:

\[
\delta = 23.45 \sin[0.9863 (284 + n_1)]
\]

where, \(\delta\) is the angle of inclination and \(n_1\) is the numerical day of the year and \(\beta\) is the orientation of the surface is towards the equator. The slope of the test modules in the present study were kept at 15\(^\circ\).

In the present study, data for different parameters, such as, inlet and outlet water temperatures, PV panel top and rear temperature, ambient temperature, water flow rate and solar radiation have been measured. For this purpose, instruments that were used for measuring different parameters and collection of experimental data. These include thermocouples (K-type), pyranometer, I-V tracer, data logger (series 3), and a computer for data acquisition can be observed in Fig. 3. Table 4 shows the range of capacities and the accuracy of the experimental observing equipment. Before for experimental study, all the measuring instruments have been properly calibrated against standard apparatus.

3. Analysis

In this work, experimental data have been collected based on the requirements for calculating the thermal, electrical energy and exergy performances. The experimental data have been gathered in three different methods. Firstly, a reference solar PV module (60 cell-Polycrystalline, 250 W) and PV/T-PCM only system was arranged and studied simultaneously under the same outdoor condition. The data had been collected with different water flow rates ranging from 0.5 to 4 LPM (litre/min).

### 3.1. Energy analysis

The thermal efficiency (\(\eta_{th}\)) of the conventional flat plate solar collector is calculated using the following formulae as shown below [44–46]:

\[
\eta_{th} = \frac{Q_{ch}}{A \times G}
\]

where, \(Q_{ch}\) is heat loss, \(A\) is area of collector and \(G\) is solar radiation.

Under these conditions, the useful collected heat (\(Q_u\)) is given by:

\[
Q_u = \left\{ mC_p(T_{Out} - T_{In}) \right\} + \left\{ m_{PCM} \times L_{PCM} \right\}
\]

where \(m\) is mass of water flow rate, \(C_p\) is temperature gradient between the thermal factor temperature at the collector exit and the point of entry, \(T_{Out}\) is outlet water temperature and \(T_{In}\) is inlet water temperature.

The phase change material (PCM) mass (\(m_{PCM}\)) can be calculated as follows:

\[
m_{PCM} = \frac{Q_{ch}}{L_f + \frac{1}{m} \int_{i}^{f} C_{p_s}(T)dT + \frac{1}{m} \int_{i}^{f} C_{p_l}(T)dT}
\]

where \(C_{p_s, p_l}\) are specific heat of solid and liquid phase of the PCM, respectively. \(L_f\) is latent heat of PCM, \(Q_{ch}\) is heat charging phase, \(m\) and \(f\) are initial, melting and final temperature of PCM, \(dT\) is the temperature rise.

A solar cell’s energy conversion efficiency is the percentage of power converted and collected equation (6).
\[ \eta_{el} = \frac{P_{moc}}{A \times G} \]  

The solar energy absorbed by the PV modules is converted into electric energy and thermal energy, but the thermal energy is dissipated by convection, condition and radiation.

### 3.2. Exergy analysis

In the following formulae, \( E_{\text{out}} \) is the maximum amount of exergy that can be obtained from a system whose supplying energy is \( E_{\text{in}} \): the energy consumed is equal to the exergy loss \( E_{\text{loss}} \), as in equation (7) [47].

\[ E_{\text{x}} - E_{\text{ex}} = E_{\text{x}} \]  

The exergy efficiency of the PV module can be expressed as the ratio of the total output and total input exergy as shown in equation (8) [47].

\[ \eta_{ex} = \frac{E_{\text{input}}}{E_{\text{output}}} \]  

Equation (9) shows the inlet exergy of a PV system which includes the only solar radiation intercity exergy.

\[ E_{\text{in}} = A \times G \times \left[ 1 - \frac{4}{3} \left( \frac{T_a}{T_c} \right) + \frac{1}{3} \left( \frac{T_a}{T_c} \right)^4 \right] \]  

The exergy output includes the thermal exergy and the electrical exergy of the PV system.

\[ E_{\text{out}} = E_{\text{thermal}} + E_{\text{electrical}} \]  

The thermal exergy can be expressed as in equation (11):

\[ E_{\text{thermal}} = Q \times \left[ 1 - \frac{T_a}{T_c} \right] \]  

where, \( Q \) is heat loss, \( T_a \) is ambient temperature and \( T_c \) is the PV cell temperature.

The overall heat loss coefficient is \( U \).

\[ Q = UA(T_c - T_a) \]  

where, \( A \) is collector area.

The overall heat loss coefficient of a PV module includes the convection and the radiation losses

\[ U = h_{\text{conv}} + h_{\text{rad}} \]  

The convective heat transfer coefficient can be written as follows:

\[ h_{\text{conv}} = 2.8 + 3.9 \nu \]  

where, \( \nu \) is the wind speed.

Radiative heat transfer coefficient between PV array and surroundings can be writing in two equations (15) and (16) [48]:

\[ h_{\text{rad,1}} = \varepsilon \sigma \left( T_{\text{sky}} + T_c \right) \left( T^2 + T_c^2 \right) \]  

\[ h_{\text{rad,2}} = 1.78 \left( T_m - T_a \right) \]  

Effective temperature of the sky

\[ T_{\text{sky}} = T_a - 6 \]  

The solar cell temperature can be calculated using equations (15)–(17) [49,50]:

\[ T_c = \frac{P_{sg} G(T_m - \eta_{el}) + (h_{\text{conv}} T_a + h_{\text{rad,2}} T_b)}{h_{\text{conv}} + h_{\text{rad,2}}} \]  

where, \( P_{sg} \) is packing factor of the solar module and \( T_b \) is the rear panel temperature.

The exergy inflow of the collector surface is given by equation (19) [45,51]:

\[ \sum E_{\text{in}} - \sum (E_{\text{in}} + E_{\text{d}}) = \sum E_{\text{ex}} \]  

\[ E_{\text{ex}} = Q_a \left( 1 - \frac{T_a + 273}{T_a + 273} \right) \]  

\[ E_{\text{d}} = \eta_{pv} \times A \times N_c \times G \times \left[ 1 - \frac{4}{3} \left( \frac{T_a}{T_c} \right) + \frac{1}{3} \left( \frac{T_a}{T_c} \right)^4 \right] \]  

\[ E_{\text{ex,net}} = E_{\text{ex}} - E_{\text{d}} \]  

where,

\[ E_{\text{in}} \] is input exergy same as equation, \( E_{\text{out}} \) is output exergy, \( E_{\text{ex}} \) is exergy, \( E_{\text{d}} \) is energy destruction, \( \eta_{pv} \) is the packing factor of the solar module and \( N_c \) is the number or quantity of collectors, \( T_i \) is sun temperature, \( E_{\text{ex}} \) is the energy destruction.

\[ \eta_{ex} = 1 - \frac{E_{\text{d}}}{E_{\text{ex}}} \]  

where, \( \eta_{ex} \) is the exergy efficiency.

The analytical parameters of the solar PV and PV/T-PCM systems are as presented in Table 5.

### 3.3. Economic analysis

Annual worth (A.W) is the difference between an annual benefit (revenue) and annual cost [52,53]. It is a gain if it is a net benefit, and a loss if it is a net loss, i.e.

\[ AW = B_A - C_A \]  

where, \( B_A \) is the annual benefit and \( C_A \) is the annual cost.

A cash flow formula (25) has been utilized for the solar collector systems related economic analysis [44].

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector area</td>
<td>( A )</td>
<td>1.64</td>
<td>m²</td>
</tr>
<tr>
<td>Number of glass cover</td>
<td>( N_1 )</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Emittance of glass</td>
<td>( \varepsilon_g )</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>Emittance of plate</td>
<td>( \varepsilon_p )</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Collector tilt</td>
<td>( \beta )</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Specific heat of working fluid</td>
<td>( C_p )</td>
<td>4183.5</td>
<td>J/kg °C</td>
</tr>
<tr>
<td>Sun temperature</td>
<td>( T_s )</td>
<td>5777</td>
<td>°C</td>
</tr>
<tr>
<td>Wind velocity</td>
<td>( u )</td>
<td>1.1</td>
<td>m/s</td>
</tr>
<tr>
<td>Transmittance</td>
<td>( \tau )</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Absorptance</td>
<td>( \alpha )</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>Packing factor of the solar module</td>
<td>( P_{sg} )</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Initial temperature</td>
<td>( T_i )</td>
<td>42.48</td>
<td>°C</td>
</tr>
<tr>
<td>Melting temperature</td>
<td>( m )</td>
<td>43.72</td>
<td>°C</td>
</tr>
<tr>
<td>Final temperature</td>
<td>( f )</td>
<td>45.76</td>
<td>°C</td>
</tr>
<tr>
<td>Latent heat</td>
<td>( L_f )</td>
<td>228.9</td>
<td>kJ/kg</td>
</tr>
</tbody>
</table>
(A/W) PV = \(-(i_c + i_c) (A/P, i, N) - A_{AC} - \left(C_{aic} \right)(A/F, i, N)\)

Solar

\begin{equation}
A/P = \frac{i(1 + i)^N}{(1 + i)^N - 1}
\end{equation}

\begin{equation}
A/F = \frac{i}{(1 + i)^N - 1}
\end{equation}

where,

- \(i_c\) is initial cost, \(i_c\) is installation cost, \(A/P\) is capital recovery factor, \(i\) is interest rate, \(N\) is life span, \(A_{AC}\) is annual running cost and \(C_{aic}\) is change of aluminum foil insulation cover.

To use the formula of equations (26) and (27), any lump-sum payments or benefits must be converted into equivalent uniform periodic time by using of the capital recovery factors \((A/P, i, N)\) and \((A/F, i, N)\).

### 3.4. Market survey

A solar energy system is generally defined by a high initial cost and low operational costs as compared with the relatively low initial cost and high operating costs of Electric Water Heater system. Heating water through solar energy also means long-term and low operational costs as compared with the relatively low.

### Table 6

The breakdown cost of solar PV module.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Retail price (MYR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV module cost</td>
<td>60 cells-Poly 250 W</td>
<td>2000</td>
</tr>
<tr>
<td>Installation cost</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Salvage Value</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total Retail Cost</td>
<td>2200 (US$ 515.81)</td>
<td></td>
</tr>
</tbody>
</table>

### Table 7

The breakdown cost of thermal collector.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Retail price (MYR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal collector</td>
<td>Absorber Aluminium sheet (1 mm, 39, 58 inch)</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>Absorber Copper Pipe (1 mm, 0.5 inch, 581 inch)</td>
<td>280.77</td>
</tr>
<tr>
<td></td>
<td>Copper Pipes elbow connector (0.5 inch dia, 68 pieces)</td>
<td>578</td>
</tr>
<tr>
<td></td>
<td>Pipe to absorber sheet gaps fill up with heat conducting paste</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Aluminium foil cover</td>
<td>30</td>
</tr>
<tr>
<td>Insulation sheet</td>
<td>Ceramic Fiber paper</td>
<td>50</td>
</tr>
<tr>
<td>Plywood sheet</td>
<td>6 mm Plywood (2.5, 3 fit)</td>
<td>30</td>
</tr>
<tr>
<td>Back cover sheet</td>
<td>Aluminium 1 mm sheet</td>
<td>36</td>
</tr>
<tr>
<td>Inlet, Outlet pipe</td>
<td>6 m palate 0.5 m dia</td>
<td>20</td>
</tr>
<tr>
<td>Gate valves</td>
<td>Mattel and plastic</td>
<td>30</td>
</tr>
<tr>
<td>Storage tank</td>
<td>80 gallon plastic tank</td>
<td>180</td>
</tr>
<tr>
<td>Water Flow meter</td>
<td>0.5 to 4 water LPM</td>
<td>250</td>
</tr>
<tr>
<td>Other</td>
<td>Pudding, Screw, Rods, Silicone paste etc.</td>
<td>200</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Salvage Value</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total Retail Cost</td>
<td>1750.77 (US$ 410.48)</td>
<td></td>
</tr>
</tbody>
</table>

### Table 8

The breakdown cost of PCM.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Retail price (MYR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCM</td>
<td>Phase change material (Lauric acid, 8.72 kg)</td>
<td>1813.76</td>
</tr>
<tr>
<td>Aluminum packets for PCM</td>
<td>7 packets</td>
<td>40</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Salvage Value</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Total Retail Cost</td>
<td>1853.76 (US$ 43153)</td>
<td></td>
</tr>
</tbody>
</table>

MYR 2000 (US$ 469.21) per unit, solar thermal collector system at MYR 1650.77 (US$ 387.33) per piece.

### 4. Results and discussion

A PV/T-PCM water collector with an innovative serpentine flow channel has been designed and fabricated and its performance has been studied as a PV/T-PCM system. The outcomes of the present research work and the corresponding explanations of the results wherever necessary. Upon design, fabrication and installation of the system, data for different parameters, like PV top surface, back surface, inlet water and outlet temperatures were collected at flow rates ranging from 0.5 to 4 L per minute (LPM). The detail results can be seen in Appendix A and B. An overall comparative study among all the systems while an economic analysis has been given in section 4.4 and 4.5.

#### 4.1. Hourly variation of PV and PV/T-PCM different parameters

Comparative performance investigation of the reference PV and PV/T-PCM systems. Hourly variation of different parameters obtained with the mass flow rate were measured 0.5, 1, 2, 3 and 4 LPM are shown in Appendix A in Figs. A.1, A.2, A.3, A.4 and A.5 respectively. From each of the figures, it can be seen that cell temperature of PV/T-PCM module is always lower than that of the PV/T only module for all the flow rates, establishing the justification of using PCM in thermal management of the PV/T system.

In Table 9 is given the details of various measured and calculated parameters for a mass flow rate of 4 LPM. It can be seen that power output (\(P_{max}\)) increases with the irradiation level and reaches to its maximum (995 W/m²) at 13:00 p.m.

Fig. 4 shows an average inlet, outlet and cell temperature differences based on mass flow rate of water. PV and PV/T-PCM cell temperature performance, which is affected on solar radiation and ambient temperature. But because of PCM and mass flow of water
the PV/T-PCM cell temperature drops significantly. The maximum cell temperature difference between PV and PV/T-PCM panels are 10.09°C, 10.26°C, 13.15°C, 12.45°C and 10.57°C respectively. Whereas the maximum rise in PV/T-PCM collector outlet water temperatures are 26.40°C, 10.09°C, 14.66°C, 10.57°C and 13.15°C respectively.

4.2. Energy analyses

The energy analysis that is based on the first law of thermodynamics presents a rough picture that shows how the input energy has been exploited and which sectors are the prime contributors in the energy consumption. In the present study, the change in different energy parameters, such as, electrical power output, electrical efficiency, thermal efficiency, etc., have been analyzed as a function of the solar irradiation, cell temperature and water flow rate in order to observe which of them has the prominent effect on the energy performance of the PV/T-PCM systems. Phase change materials (PCM) are substances that possess high heat of fusion. These materials can store (or release) huge amount of energy as latent heat during their freezing (or melting) process, the heat being taken from the surrounding environment. When the surrounding temperature of a solid PCM reaches its melting point, it starts to absorb heat from the ambient, gets molten and stores this energy as latent heat as long as the surrounding temperature is above its melting point. On the other hand, when again the surrounding temperature falls and come near the freezing point, PCMs release the stored energy and gets solidified. It may be mentioned here that an experimental study on PV/T-PCM has been carried out for five different flow rates of cooling water, however, representative results of an optimum flow rate have only been presented in the forthcoming sections.

4.2.1. Effect of irradiation and cell temperature on electrical performance

The effect of increased irradiation and cell temperature level on electrical power and electrical efficiency has been illustrated in Appendix B. The results shows that the effect of increased irradiation and cell temperature level on electrical power and electrical efficiency at the mass flow rate of 0.5 LPM. The peak solar radiation is 999 W/m², the electrical power of the PV and PV/T-PCM module is 140.64 W and 151.26 W respectively as shown in Fig. B.1. The maximum difference between the output power of PV and PV/T-PCM is 18.28 W at 10:45 a.m. The maximum difference between electrical efficiency of PV and PV/T-PCM module is 2.14% at 10:45 a.m. The maximum electrical efficiency of the PV/T-PCM is 13.92% at 10:15 a.m. The experimental investigation has been carried out on-site under real ambient conditions, wherein the radiation intensity at any time may go down due to shading from cloud, etc. The data acquisition is a continuous process in which some irregular data may also be saved. These irregular data do not show the trend.

Figs. A.1 and B.1 shows that solar radiation reaches its peak of 999 W/m², the ambient temperature to 36.52 °C and the maximum cell temperature difference to 4.71 °C at 10:09 a.m. PV/T-PCM output power is observed to increase by 10.09 W at 2:15 p.m. As can be seen power difference between PV and PV/T-PCM because of the effect of cell temperature (as explained above). At low mass flow rate (0.5 LPM), cell temperature is dropped very little for PV/T-PCM system. As a result, PV/T-PCM system produce little amount of power. The variation in the PV and PV/T-PCM efficiency is from 0.40% to 2.14%. On the other hand, cell temperature variation is 4.16°C for PV and PV/T-PCM, respectively.

Fig. B.2 shows the effect of irradiation level on electrical power flow rate have only been presented in the forthcoming sections.

4.2. Energy analyses

The energy analysis that is based on the first law of thermodynamics presents a rough picture that shows how the input energy has been exploited and which sectors are the prime contributors in the energy consumption. In the present study, the change in different energy parameters, such as, electrical power output, electrical efficiency, thermal efficiency, etc., have been analyzed as a function of the solar irradiation, cell temperature and water flow rate in order to observe which of them has the prominent effect on the energy performance of the PV/T-PCM systems. Phase change materials (PCM) are substances that possess high heat of fusion. These materials can store (or release) huge amount of energy as latent heat during their freezing (or melting) process, the heat being taken from the surrounding environment. When the surrounding temperature of a solid PCM reaches its melting point, it starts to absorb heat from the ambient, gets molten and stores this energy as latent heat as long as the surrounding temperature is above its melting point. On the other hand, when again the surrounding temperature falls and come near the freezing point, PCMs release the stored energy and gets solidified. It may be mentioned here that an experimental study on PV/T-PCM has been carried out for five different flow rates of cooling water, however, representative results of an optimum flow rate have only been presented in the forthcoming sections.

![Fig. 4. Average inlet outlet water and cell temperature different PV and PV/T-PCM parameters (0.5—4 LPM).](image)
and electrical efficiency at mass flow rate of 1 LPM. The highest solar radiation attained is 988 W/m², at which the electrical power of the PV and PV/T-PCM module is 138.40 W and 145.45 W respectively. The maximum difference between the output power of PV and PV/T-PCM is 24.97 Wat 2:15 p.m. From Fig. B.2 it can be observed that the maximum electrical efficiency of the PV/T-PCM is 14.25% at 3:45 p.m. Also, the maximum electrical efficiency difference between PV and PV/T-PCM module is 1.55% at 2:15 a.m. The irradiation level increases rapidly at the early part of the day, while during midday the variation becomes minute. That is why, the electrical power and efficiency remain almost same near an average value.

Under the peak solar radiation of 988 W/m² at 1:30 p.m. the ambient temperature is 36.34 °C and cell temperature difference is 7.03 °C, whereas the increase in PV/T-PCM power output is 7.05 W, respectively as shown in Fig. A.2 and B.2. When the mass flow rate is increased from 0.5 to 1.0 LPM, cell temperature for PV/T-PCM system lower as compared to that at 0.5 LPM. After that the cell temperature is observed to up and down and the power reached at maximum level 24.97 W. It is also observed that around 1:45 to 2:45 p.m., the solar radiation was high. Because of PCM, the cell temperature is dropped suddenly and it maintains a little time then again back to its original trend. The variation in the PV and PV/T-PCM is from 0.05% to 1.55%, while the cell temperature variation 5.08 °C–6.40 °C respectively.

Fig. B.3 presents the electrical power and electrical efficiency of PV/T-PCM systems at a mass flow rate of 2 LPM. The electrical power of the PV and PV/T-PCM module are 133.39 W and 150.06 W respectively under the peak radiation of 983 W/m². The maximum electrical efficiency of the PV/T-PCM is 13.04% at 10:15 a.m. In addition, the maximum electrical efficiency difference between PV and PV/T-PCM module is 2.33% at 3:15 p.m.

The ambient temperature is 35.21 °C, and cell temperature difference is 5.64 °C and the increase in PV/T-PCM is 16.67 W under the peak radiation of 983 W/m² at 12:00 noon as shown in Figs. A.3 and B.3. As the mass flow rate increases from 1 to 2 LPM, the cell temperature of PV/T-PCM collector drops are high and output power increases as compared mass flow rate of 0.5 and 1 LPM respectively. Because of increasing mass flow rate with PCM cooling capacity. It is observed, PV/T-PCM maximum power found 21.71 W at cell temperature of 7.98 °C. Fig. B.3 also reveals that the variation in the PV and PV/T-PCM is from 0.18% to 2.33%, while the cell temperature variations are 13.15 °C–9.33 °C respectively.

Electrical power and efficiencies at mass flow rate of 3 LPM are shown in Fig. B.4. At the peak solar radiation of 989 W/m², the electrical power of the PV and PV/T-PCM module are 116.62 W and 130.76 W respectively. The maximum output power for PV/T-PCM module is 140.70 W at 3:00 p.m. On the other hand, the maximum electrical efficiency of PV/T-PCM system is 13.90% at 10:30 a.m. Furthermore, from Fig. B.4 is seen that the maximum electrical efficiency difference between PV and PV/T-PCM module is 1.74% at 12:00 p.m.

For PV/T-PCM system, the ambient temperature is 37.26 °C, cell temperature difference is 6.53 °C and the increases in output power is 14.13 W at peak radiation of 989 W/m² at 1:45 p.m. as shown in Figs. A.4 and B.4. As the mass flow rate increases from 2 to 3 LPM, the cell temperature of PV/T-PCM drop is little as compared that of 2 LPM. The maximum power is found 25.10 W at cell temperature of 3.93 °C. Furthermore, the variation in the PV and PV/T-PCM is from 0.45% to 1.74%, while the cell temperature variation 4.06 °C–5.06 °C respectively.

The effect of increased irradiation level on electrical power and electrical efficiency has been illustrated in Fig. B.5 at optimum mass flow rate of 4 LPM. It can be seen from Fig. B.5 that electrical power and efficiency of PV/T-PCM systems increases with increasing irradiation level. In both cases, it surpasses the power output of the reference PV system over the full range of irradiation as can be seen from Fig. B.5. Firstly, the effect of cooling becomes effective at higher irradiances that is portrayed by the expanding gap between the trend lines of PV and PV/T-PCM systems. The temperature difference between the inlet water and outlet water is very trivial at lower radiation level. As the irradiation level increases, the temperature difference increases to mobilize the rate of heat transfer, which helps to remove more heat from the higher irradiances. This tendency is slightly greater in the case of the PV/T-PCM system, evidently indicating the practical usage of the PCM in temperature control.

Secondly, the increment rate of power output is steeper in the range of around 300–1000 W/m², after which the effect of increased irradiation own diminished. Hence, it may be concluded that the highest output from a PV/T or PV/T-PCM panel in typical Malaysian weather condition can be obtained under irradiation of around 1000 W/m². Thirdly, at 992 W/m², the electrical power of the PV and PV/T-PCM module is 123.85 W and 160.29 W respectively, which is cleared enhancement in the power output with the PCM and mass flow rate used for thermal control. Results show that power levels of solar cell vary under different levels of illuminations. Panel current increases in proportional to solar radiation with little increases in panel voltage. Similarly, panel power increases in proportion to solar radiation level. The difference between maximum output power of PV and PV/T-PCM is 36.44 W at 1:00 p.m. For every 100 W/m² increase in irradiation level, output power rose by 13.12 W for PV/T-PCM respectively. Phase change materials possess a good ability of storing large amount of heat, which helps to lower the cell temperature and keeps as near as possible to the STC value, thereby improving the electrical output. Fig. B.5 show the response of electrical efficiency as a function of the irradiation of PV/T-PCM systems respectively both on the performance of the same reference PV module. It is evident from the Fig. B.5 that the efficiency of all types of photovoltaic devices, PV and PV/T-PCM, increases up to an irradiation level of around 300–600 W/m², which then drops significantly with increased irradiation. Therefore, photovoltaic devices perform best under the above-mentioned range of irradiation in Malaysian condition. While the proposed PV/T-PCM system show better electrical efficiency than the reference PV module. As the irradiation level increases from 375 to 992 W/m², electrical efficiency drops from 12.88% to 9.78% for PV/T-PCM module and 12.41%–7.56% for PV module. The maximum difference between PV and PV/T-PCM system is 2.48% at 11:15 a.m. It may be noticed from and that maximum electrical efficiency of the PV/T-PCM is 14.42% at 3:15 p.m., which evidently shows distinctive improvement in the electrical performance by employing PCM. For PV/T-PCM modules every 100 W/m² increase in irradiation level, electrical efficiency drops by 0.55% respectively. This holds good not only for the maximum point, but also for almost the entire range of efficiency, which further establishes the appropriate choice of employing the PCM thermal control in the PV/T systems.

The adverse effect of increased cell temperature in electrical power output of the PV/T-PCM systems is apparently conceivable from Fig. B.5 in which it is readily observed that the corresponding power drop in the PV/T-PCM system is greater than that of the PV system for almost the same temperature rise. The reason behind the alternation in power level is that panel temperature leads to a little increase in panel current while it decrease the panel voltage proportionally. Panel power decrease since the voltage decrease
rate is more than the increase in current rate. On the other hand, increase in module temperature reduce the band gap of a solar cell, whereby effecting the solar cell output parameters. Open circuit voltage the most affected parameter due to increase in temperature. Figs. A.5 and B.5 shows the tendency for PV/T-PCM and PV reference. At 992 W/m², the ambient temperature was 35.36 °C and the cell temperature difference were 3.33 °C and the output power difference was 36.44 W at 1:00 p.m. The cell temperature and output power vary because of mass flow rates and PCM cooling capacity. For every 1 °C decrease in cell temperature, output power increases by 8.76 W for PV/T-PCM systems respectively.

Drop in the electrical efficiency due to the cell temperature rise is less prominent in photovoltaic thermal systems, especially in the case of a PV/T-PCM system. This is due to the fact that PCMs can exert a better control over the cell temperature rise by its intrinsic ability in absorbing a large amount of heat through alternate melt/ freeze cycles at a particular range of temperature. It may be perceived from Fig. B.5 that the variation in the PV and PV/T-PCM is from 0.48% to 2.48% respectively. In addition, electrical efficiency of the PV/T-PCM is higher than the PV efficiency demonstrating the favorable effect of cooling. During afternoon, PV/T-PCM system works with efficiencies as high as 13.82% or more. For every 1 °C decrease in cell temperature, efficiency increases by 0.37% for PV/T-PCM systems respectively. Another notable point from these Figs. B.1–B.5 is that for both the power output and the efficiency curves, the gap between the PV and the PV/T-PCM trend lines is wider. This portrays a better relative improvement in both the electrical power and the efficiency of the PV/T-PCM system than that of the PV module. This finding also confirms that the PV/T-PCM system has a superior performance.

Fig. 5 shows an average PV and PV/T-PCM electrical efficiency and power differences based on mass flow rate of water. PV/T-PCM module electrical efficiency and output power increases because of mass flow rates and PCM cooling capacity.

4.2.2. Effect of water flow rate on thermal performance

Photovoltaic thermal (PV/T) collectors, as the name implies, are meant for thermal output along with electricity. Moreover, there is a material limit for silicon cells, especially, in terms of life span, after which the electrical performance cannot be improved. On the other hand, there are wide provisions for improvement in the thermal performance by adopting effective thermal energy harvesting techniques. For this particular reason, the thermal performance of PV/T-PCM collectors is of great importance which needs to be investigated thoroughly. Thermodynamic performance of any system can be analyzed from two different viewpoints, i.e., one is based on the first law of thermodynamics while the other is its second law. Energy analysis of PV/T-PCM systems only based on

Fig. 5. Average electrical power and efficiency different PV and PV/T-PCM parameters (0.5–4 LPM).

Fig. 6. Effect of water flow rate on thermal performance of PV/T-PCM collector (a): Thermal efficiency and heat gain (b): Inlet and outlet temperatures.
the first law of thermodynamics has been discussed in this section and second law-based analysis, i.e., exergy analysis which is elaborated in the following section. In both cases, variation in performance parameters have been presented as a function of the mass flow rate of heat transfer fluid (HTF), namely, water.

Thermal performances of PV/T-PCM systems have been illustrated in Fig. 6 (a), respectively wherein the performance has been portrayed in terms of heat gain, thermal efficiency and outlet water temperature. Although PV/T-PCM collectors are meant for both electricity and heat productions, one of the major applications of these devices are in warm water supply. Hence, together with heat gain and thermal efficiency of the device, the level of outlet water temperature has been used here as an index for the thermal performance.

Fig. 6 (a) present the heat gain as well as the thermal efficiency of PV/T-PCM modules, respectively. It can be noticed that both the heat gain and the thermal efficiency follows the trend of a bell-shaped curve although the distribution of the values are not the same nor symmetrical. This trend signifies the fact that there is an optimum flow rate at which the peak performance is obtained. For the PV/T-PCM modules provide as high as 1024.01 W with a thermal efficiency of 87.71% at 2 LPM. Hence, the use of PCM can conveniently provide 164.09 W more heat gain capacity.

Fig. 6 (b) show the outlet water temperature along with the inlet water temperature produced by the PV/T-PCM systems, respectively. It is obvious that the outlet water temperature decreases gradually with increasing water flow rate which is evident from both Fig. 6 (a) and 6 (b). Hence, in order to get warm water supply with better thermal efficiency, the flow rate should be maintained between 1 and 2 LPM. Another revealing fact from Fig. 6 (b) is that the PV/T-PCM system provides relatively lower outlet water temperature, which is due to the system’s huge thermal storage capacity. However, the major benefit of PCM thermal storage is in its extended period of availability of heat which makes the PV/T-PCM modules highly favorable for night time energy supply.

4.3. Exergy analysis of PV/T-PCM systems

The limitation of the first law of thermodynamics analysis is that it does not account for the energy quality, rather all forms of energies, viz., electric, mechanical, chemical, thermal energy, all of which have values leading to a wrong assessment. The second law of thermodynamics comes to help in this context introducing the concept of exergy which is the thermodynamic property of combined energy quantity and quality to portray the real picture of the energy utilization efficiency. Exergy is the maximum useful work obtainable from a system during a process when the system is brought to an equilibrium with a heat reservoir. In other words, exergy is defined as the maximum amount of work that can be produced from a flow of mass or energy as it comes into an equilibrium with a reference environment. Therefore, the exergy performance of the PV/T-PCM systems have been evaluated in this section to gauge their actual working efficiency.

Fig. 7 show the exergy output and exergy efficiency of the PV/T-PCM systems, respectively. It may be noticed from the Fig. 7 that exergy output becomes almost constant after a certain flow rate of 2 LPM for the PV/T-PCM systems. The highest exergy output obtained with the PV/T-PCM is 134.10 W respectively. On the other hand, exergy efficiency keeps on decreasing with increasing water flow rate which is due to the fact that with an increased flow rate of a volume of water the irreversibility increases substantially causing greater exergy destruction. Hence, higher exergy efficiency is attainable at lower flow rates. The highest exergy efficiency obtained with the PV/T-PCM is 12.19% respectively.

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4.4. Comparative performance evaluation

In this section, the performances of a PV/T-PCM system have been presented in comparison with a reference PV performance so that a relative ranking among the devices is possible. Fig. 8 shows the performance of the PV/T-PCM system in comparison with the reference PV performance in which 11.08% electrical efficiency of the PV/T-PCM is observed to increase by 1.20% as compared to the reference PV performance in which 11.08% electrical efficiency of the PV/T-PCM is enhanced by more than 5% as compared to the PV exergy efficiency. From Table 10, it can be noticed that an exergy output of PV/T-PCM is increased by 58.89% as compared to the reference PV.

4.5. Economic analysis

An economic analysis mainly discusses the payback period of the system which can be separated into two parts, i.e., the first is the solar PV panel and the second is the PV/T-PCM system. These results can project a clear understanding between the renewable and the nonrenewable economic performances. From equations (25)–(27), it is possible to forecast the results from the assumed years to draw a cash flow diagram for a solar PV panel system and to calculate the total cost on a period of 6 years lifespan. Data from Tables 5–7 are required to calculate the module’s lifespan at 10% interest rates of the cash flow. This analysis used some assumed values to arrive at some pragmatic amount.

<table>
<thead>
<tr>
<th>Average</th>
<th>PV</th>
<th>PV/T-PCM (optimum)</th>
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</thead>
<tbody>
<tr>
<td>Electrical efficiency (%)</td>
<td>9.75</td>
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</tr>
<tr>
<td>Thermal efficiency (%)</td>
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</tr>
<tr>
<td>Exergy efficiency (%)</td>
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<td>12.19</td>
</tr>
<tr>
<td>Exergy out (W)</td>
<td>75.21</td>
<td>134.10</td>
</tr>
</tbody>
</table>

(A) Cash Flow diagram for solar PV panel as flows:
Fig. 9 illustrates the cash flow diagram of a solar PV module from year 0 to year 25 with values and arrows showing the year and cost per 5-year period of MYR 100 (US$ 23.46). Zero is the initial year, thus, MYR 2000 (US$ 469.25) is the initial cost plus MYR 100 (US$ 23.46) as the installation cost. Whereas the annual running cost is zero. After 15 and 25 years later, MYR 100 (US$ 23.46) extra is added for some additional replacement of component parts.

Cost of using a solar PV panel:
For the first 5 years:
A,W(\text{Solar PV}) = MYR -570.35 (US$ 133.82)
For the 6 years of usage:
A,W(\text{Solar PV}) = MYR -495.13 (US$ 116.22)
For the 15 years of usage:
A,W(\text{Solar PV}) = MYR -279.24 (US$ 65.51)
For the 25 years of usage:
A,W(\text{Solar PV}) = MYR -1816.05 (US$ 434.35)

For annual benefit calculation, the average PV power output for 6 h data has been taken form the experiment result. It is calculated, the 6 years cost benefit for PV panel is RM 524.25 (US$ 123.06), where cost of one unit (1 kW) of electricity in Malaysia is MYR 0.3853 [54]. From the equation (24), it is calculated, the payback period for PV panel is 6 years.

(B) Cash Flow diagram for solar PV/T-PCM system as flows:
The thermal absorber and PCM materials costs are MYR 1750.77 (US$ 410.22) and MYR 1853.76 (US$ 434.35), respectively. Fig. 10 illustrates the cash flow diagram of a PCM from year 0 to year 25 with values and arrows showing the year and cost per 5-year period of MYR 1900 (US$ 445.22). From Tables 5–7, states that zero cost is encountered in the initial year, thus, MYR 5604.53 (US$ 1313.29) is the initial cost plus MYR 1900 as the installation cost. Whereas the annual running cost is zero while the PV/T-PCM materials 5 years later will need to be replaced costing MYR 1900 (US$ 445.22) extra which is added to the additional replacement of some component parts.

Cost of running a PV/T-PCM system:
For the first 4 years:
A,W(\text{Solar PV/T-PCM}) = MYR -2209.00 (US$ 518.54)
For the first 5 years:
A,W(\text{Solar PV/T-PCM}) = MYR -1816.05 (US$ 434.35)
For the 10, 15, and 20-year period:
A,W(\text{Solar PV/T-PCM}) = MYR -1047.60 (US$ 245.51) for 10-year period, MYR -809.79 (US$ 189.77) for the 15-year period, and MYR -703.22 (US$ 164.78) for the 20-year period.
For the 25th year period:
A,W(\text{Solar PV/T-PCM}) = MYR -3320.61 (US$ 779.48).

It is assumed that at the 25th year the solar PV panel will again incur a cost of MYR 100 (US$ 23.46) for additional replacement of component parts: MYR -232.36 (US$ 54.51).

For annual benefit calculation, the average PV power output for 6 h data has been taken form the experiment result. From the equation (24), the solar PV/T-PCM system cost is definitely high as compared to the solar PV system, but after 4 years of usage, the cost benefit value becomes MYR 3320.61 (US$ 779.48). The annual worth for the PV/T-PCM module is MYR 1111.61. That means the PV life cycle can be improved and used for a lower period. The result shows that the solar PV/T-PCM system can be used for a longer lifespan than the solar PV/T system.
5. Conclusions

The purpose of this study was to investigate the performance of a newly developed PV/T-PCM module for use under typical Malaysian weather condition. Energy, exergy and economic analyses have been conducted to analyze the total performance of the system from technical as well as economic viewpoints. Comparative analysis was performed in the following manner: The performance of a PV/T-PCM system has been compared with that of a reference PV module.

For PV/T-PCM system, both the maximum electrical power output and the maximum efficiency are obtained at 4 LPM. The maximum power output is 160.29 W, which is almost 14% higher than that of the reference PV module. The maximum electrical efficiency is 14.42%, which is 4.72% higher than that of the reference PV. For every 100 W/m² increase in irradiation level, PV/T-PCM power output increases by 13.12 W, while electrical efficiency drops by 0.55%. Every 1 °C decrease in PV/T-PCM cell temperature is followed by an increase in output power by 8.76 W and electrical efficiency by 0.37%. The maximum PV/T-PCM thermal efficiency is 87.72% with a mass flow rate of 2 LPM, while the highest rise obtained is 26.40 °C at 0.5 LPM. The maximum PV/T-PCM exergy output of 134.10 W is attained at 0.5 LPM and the maximum average exergy efficiency of 12.19% is obtained at a mass flow rate of 1 LPM.

The breakdown cost of a solar PV module is RM 2000 (US$ 469.25) which is expensive but because of its long-term use, it will be free of maintenance costs as based on the Annual-worth methods from 5 to 10 years later. A phase change material costs approximately MYR 5604.53 (US$ 1313.29) which is considered as a high investment cost but which can be free of maintenance costs after usage of up to 4 years. PCM materials need to change every 5 or 6 years later which means that one time investment can last at least up to 5 years. If the system cost together with the installation cost come around MYR 1900 (US$ 445.22), and after usage of up to 4 years as based on the Annual-worth methods, then the cost benefit will be MYR 3320.61 (US$ 779.48). The results of calculations on the cost analyses show that the PV/T-PCM systems are more economical and become more attractive than the solar PV system operating alone in the long run, thus, it is advantageous for the household family to use the solar water heater which can last up to a period of at least 5 years.

Acknowledgements

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Appendix A. Hourly variation of different PV and PV/T-PCM parameters

Fig. A.1. Hourly variation of different PV and PV/T-PCM parameters (0.5 LPM).
Fig. A.2. Hourly variation of different PV and PV/T-PCM parameters (1 LPM).

Fig. A.3. Hourly variation of different PV and PV/T-PCM parameters (2 LPM).
Fig. A.5. Hourly variation of different PV and PV/T-PCM parameters (4 LPM).

Fig. A.4. Hourly variation of different PV and PV/T-PCM parameters (3 LPM).

Appendix B. Effect of irradiation and cell temperature on electrical performance of PV/T-PCM against the reference PV

Fig. B.1. Effect of irradiation and cell temperature on electrical performance of PV/T-PCM against the reference PV (0.5 LPM).

Fig. B.2. Effect of irradiation and cell temperature on electrical performance of PV/T-PCM against the reference PV (1 LPM).
Fig. B.3. Effect of irradiation and cell temperature on electrical performance of PV/T-PCM against the reference PV (2 LPM).

Fig. B.4. Effect of irradiation and cell temperature on electrical performance of PV/T-PCM against the reference PV (3 LPM).

Fig. B.5. Effect of irradiation and cell temperature on electrical performance of PV/T-PCM against the reference PV (4 LPM).