Hydrogen production with a photovoltaic thermal system enhanced by phase change materials, Shiraz, Iran case study

M. Babayan a,*, A.E. Mazraeh a, M. Yari b,**, Nima A. Niazi c, Suvash C. Saha d

a Young Researchers and Elite Club, Maragheh Branch, Islamic Azad University, Maragheh, Iran
b Department of Mechanical Engineering, University of Tabriz, Tabriz, Iran
c Department of Mechanical Engineering, Islamic Azad University Tehran Central Branch, Tehran, Iran
d School of Mechanical and Mechatronic Engineering, Faculty of Engineering and Information Technology, University of Technology Sydney, Ultimo, NSW, 2007, Australia

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A B S T R A C T

Whereas Photovoltaic Thermal Systems (PVT), Phase Change Materials (PCM) and Proton Exchange Membrane (PEM) electrolyzer have been thoroughly studied individually, the effects of their combination need to be more investigated. The current study proposed a new PVT system integrated with PCM and PEM electrolyzer to produce hydrogen in a hydrogen fuel filling station. Based on the energy and exergy balance equations, a mathematical model is developed to analyse the effects of different types of PV and PCM sets on the thermal and electrical performances. Variations in the temperature of system components, generated electricity, hydrogen production as well as the energy/exergy amounts and efficiencies with time are presented for different effective parameters. Based on the obtained results, we found that PV type is one of the most dominant parameters of the system. PCM utilization improves the electrical, thermal energies and exergy efficiencies. The highest daily amount of produced hydrogen is obtained for 16th August 2018 with mono-crystalline semitransparent PV and 120 kg of RT35 PCM type (88.71 gr/day). While the hydrogen production for the same PVT system without PCM is 5.32% less than the case with PCM. Moreover, the maximum diurnal energy efficiency is obtained 35.04% for mono-crystalline semitransparent PV and RT35 PCM during the summer, while the maximum daily exergy efficiency of 15.17% is achieved for the integration of mono-crystalline semitransparent PV and RT28 PCM type in the winter.

1. Introduction

Generally, the continuous use of fossil fuels such as oil, gas, and coal gives rise to the depletion of natural resources as well as the environmental problems like greenhouse effects. To provide rapid growing energy demands for both transportation and domestic applications, a number of environmentally benign technologies are under progress. In order to tackle these problems, renewable energies, such as solar and wind energies, biofuels, and hydrogen have been developed (Sampathkumar et al., 2010).

Solar energy is one of the most reasonable sources of renewable energy that has been utilized in numerous applications including solar stills (Abu-Hijleh, 1996) and generating electricity (Elnozahy et al., 2016). Photovoltaic and thermal systems (PVT) are among the most primary solar technologies, not only convert the solar energy to the electrical power, but produce thermal energy as well (Nemati et al., 2018). As the temperature of Photovoltaic (PV) panel increases by receiving solar radiation, the electrical power production decreases about 0.2–0.5% per each Celsius degree (Tiwari and Dubey, 2009). Therefore, in order to improve the performance of PV modules, the temperature regulation usually performed by air or water cooling techniques, seems to be necessary. The surplus extracted heat from PV panels can supply the thermal energy required for various industrial or domestic applications. This kind of system providing simultaneous thermal and electrical energy, is called PVT system. Several experimental and numerical investigations have been carried out to analyse the co-generation of heat and power by the solar units. The first PVT collector utilizing water as a coolant was proposed in 1978 (Kern and Russell, 1978).

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Krauter (2004) showed that the water flow over the PV panel decreases the reflection of sun’s irradiance and the PV temperature by 2–3.6% and up to 22 °C, respectively. Furthermore, water flow increases the electrical power by 10.3%. Kalogirou and Tripanagnostopoulos (2006) considered a domestic photovoltaic thermal system producing a considerable amount of thermal and electrical energy for a block of flats or a small office building. Aste et al. (2012) investigated a hybrid PVT system from the viewpoints of energy and economics to find out the optimal values for solar fraction. They found that the thermal solar fraction for a hybrid PVT system is around 40–60% depending on the system type. Yari et al. (2016) equipped a conventional solar still with semitransparent photovoltaic and evacuated tube collector to produce potable water and electricity in distant areas. Using 30 evacuated tubes and applying numerical solving methods, they reported the maximum water production rate and daily electrical production rate.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
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<tbody>
<tr>
<td>a</td>
<td>width of water channel (m)</td>
</tr>
<tr>
<td>A_{ab}</td>
<td>surface area of absorber channel (m²)</td>
</tr>
<tr>
<td>A_{PCM}</td>
<td>surface area of PCM set (m²)</td>
</tr>
<tr>
<td>A_{PV}</td>
<td>surface area of PV module (m²)</td>
</tr>
<tr>
<td>A_{tank}</td>
<td>surface area of water storage tank (m²)</td>
</tr>
<tr>
<td>b</td>
<td>height of water channel (m)</td>
</tr>
<tr>
<td>(\theta_0)</td>
<td>the incidence angle modifier coefficient</td>
</tr>
<tr>
<td>(c_{l,PCM})</td>
<td>specific heat capacity of liquid PCM (J/kg K)</td>
</tr>
<tr>
<td>(c_{s,PCM})</td>
<td>specific heat capacity of solid PCM (J/kg K)</td>
</tr>
<tr>
<td>(C_PV)</td>
<td>specific heat capacity of the PV module (J/kg.K)</td>
</tr>
<tr>
<td>(C_w)</td>
<td>specific heat capacity of water (J/kg K)</td>
</tr>
<tr>
<td>D_e</td>
<td>equivalent diameter of water channel (m)</td>
</tr>
<tr>
<td>dt</td>
<td>small time interval (s)</td>
</tr>
<tr>
<td>E_{el}</td>
<td>output electrical energy (W)</td>
</tr>
<tr>
<td>E_{el,daily}</td>
<td>daily electrical energy output (W)</td>
</tr>
<tr>
<td>E_{in}</td>
<td>overall input energy (W)</td>
</tr>
<tr>
<td>E_{out}</td>
<td>overall output energy (W)</td>
</tr>
<tr>
<td>E_{in,th}</td>
<td>output thermal energy (W)</td>
</tr>
<tr>
<td>E_{out,th}</td>
<td>overall output energy (W)</td>
</tr>
<tr>
<td>E_{th}</td>
<td>overall thermal energy (W)</td>
</tr>
<tr>
<td>(f)</td>
<td>gravitational acceleration (m²/s)</td>
</tr>
<tr>
<td>Gr</td>
<td>Grashof number based on tube inner diameter (-)</td>
</tr>
<tr>
<td>H_{tank}</td>
<td>height of the tank</td>
</tr>
<tr>
<td>(h_{ab,PCM})</td>
<td>overall heat transfer coefficient from absorber plate to PCM set (W/m² K)</td>
</tr>
<tr>
<td>(h_{ab,w})</td>
<td>overall heat transfer coefficient from absorber plate to water (W/m² K)</td>
</tr>
<tr>
<td>(h_{PV,a})</td>
<td>overall heat transfer coefficient from PV module to absorbent (W/m² K)</td>
</tr>
<tr>
<td>(h_{PV,ab})</td>
<td>overall heat transfer coefficient from PV module to absorber plate (W/m² K)</td>
</tr>
<tr>
<td>(h_{PV-sky})</td>
<td>overall heat transfer coefficient from PV module to sky (W/m² K)</td>
</tr>
<tr>
<td>(h_{PV-water})</td>
<td>overall heat transfer coefficient from PV module to water (W/m² K)</td>
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<tr>
<td>I(t)</td>
<td>solar radiation (W/m²)</td>
</tr>
<tr>
<td>(k_{bg})</td>
<td>thermal conductivity of back glass (W/m K)</td>
</tr>
<tr>
<td>(k_g)</td>
<td>thermal conductivity of front glass (W/m K)</td>
</tr>
<tr>
<td>(k_m)</td>
<td>thermal conductivity of insulation (W/m K)</td>
</tr>
<tr>
<td>(k_{PCM})</td>
<td>thermal conductivity of PCM (W/m K)</td>
</tr>
<tr>
<td>(k_w)</td>
<td>thermal conductivity of water (W/m K)</td>
</tr>
<tr>
<td>(\phi)</td>
<td>the incident angle modifier</td>
</tr>
<tr>
<td>(l_{bg})</td>
<td>thickness of back glass (m)</td>
</tr>
<tr>
<td>(l_g)</td>
<td>thickness of front glass (m)</td>
</tr>
<tr>
<td>(l_{PCM})</td>
<td>thickness of PCM (m)</td>
</tr>
<tr>
<td>(l_{in})</td>
<td>thickness of insulation (m)</td>
</tr>
<tr>
<td>L_{PCM}</td>
<td>PCM heat of fusion (J/kg)</td>
</tr>
<tr>
<td>m_{PV}</td>
<td>the PV module mass (kg)</td>
</tr>
<tr>
<td>m_w</td>
<td>the mass flow rate of cooling water (kg/s)</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number (-)</td>
</tr>
<tr>
<td>P_{pump}</td>
<td>DC pump power</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandlt number (-)</td>
</tr>
<tr>
<td>Q_{PCM}</td>
<td>the energy stored at the PCM set</td>
</tr>
<tr>
<td>Q_{w}</td>
<td>transferred heat to the water</td>
</tr>
<tr>
<td>Q_{w1}</td>
<td>transferred heat to the water per area</td>
</tr>
<tr>
<td>Ra</td>
<td>Rayleigh numbers (-)</td>
</tr>
<tr>
<td>RT</td>
<td>Organic PCM series</td>
</tr>
<tr>
<td>T_0</td>
<td>standard test condition temperature (K)</td>
</tr>
<tr>
<td>T_a</td>
<td>ambient temperature (K)</td>
</tr>
<tr>
<td>T_ab</td>
<td>temperature of absorber channel (K)</td>
</tr>
<tr>
<td>T_{in}</td>
<td>melting point of PCM (°C)</td>
</tr>
<tr>
<td>T_{PCM}</td>
<td>PCM temperature (K)</td>
</tr>
<tr>
<td>T_{PV}</td>
<td>PV module temperature (K)</td>
</tr>
<tr>
<td>T_{sky}</td>
<td>sky temperature (K)</td>
</tr>
<tr>
<td>T_{tank}</td>
<td>temperature of water storage tank (°C)</td>
</tr>
<tr>
<td>T_{w}</td>
<td>water temperature (K)</td>
</tr>
<tr>
<td>U_{tank-w}</td>
<td>overall heat transfer coefficient from water tank to ambient (W/m² K)</td>
</tr>
<tr>
<td>v</td>
<td>wind velocity (m/s)</td>
</tr>
<tr>
<td>w</td>
<td>width of PV panel (m)</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>water channel aspect ratio (-)</td>
</tr>
<tr>
<td>(\eta_{ab})</td>
<td>absorptivity of absorber plate (-)</td>
</tr>
<tr>
<td>(\eta_{PV})</td>
<td>absorptivity of PV module (-)</td>
</tr>
<tr>
<td>(\beta)</td>
<td>packing factor (-)</td>
</tr>
<tr>
<td>(\theta_0)</td>
<td>temperature coefficient of the PV module in the standard test condition (-)</td>
</tr>
<tr>
<td>(\Delta H)</td>
<td>the splitting reaction enthalpy of water</td>
</tr>
<tr>
<td>(\epsilon_g)</td>
<td>emissivity of glass cover (-)</td>
</tr>
<tr>
<td>(\epsilon_{PV})</td>
<td>effective emissivity of PV module (-)</td>
</tr>
<tr>
<td>(\eta_0)</td>
<td>PV module efficiency in the standard test condition (-)</td>
</tr>
<tr>
<td>(\eta_{el,daily})</td>
<td>daily electrical energy efficiency (-)</td>
</tr>
<tr>
<td>(\eta_{th,daily})</td>
<td>daily thermal energy efficiency (-)</td>
</tr>
<tr>
<td>(\eta_{el,th})</td>
<td>electrical exergy efficiency (-)</td>
</tr>
<tr>
<td>(\eta_{th,th})</td>
<td>thermal exergy efficiency (-)</td>
</tr>
<tr>
<td>(\eta_{PV})</td>
<td>PV module efficiency (-)</td>
</tr>
<tr>
<td>(\lambda_{eff})</td>
<td>effective vertical thermal conductivity (W/m.K)</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>Stefan Boltzmann constant (5.6697 × 10⁻⁸ W/m² K⁴)</td>
</tr>
<tr>
<td>(\tau_g)</td>
<td>transmissivity of glass</td>
</tr>
</tbody>
</table>

Subscripts:
- a: ambient air
- ab: absorber channel
- in: insulation
- PCM: PCM set
- PV: PV module
- w: water
power at the basin water depth of 0.07 are 4.77 kg/m²-day and 483.2 Wh/m², respectively.

Thermal energy storage (TES) systems play an important role in the reduction of building dependency on fossil fuels and gas emissions control, as well as according to energy supply and demand (Mehling and Cabeza, 2008). Phase change material is a type of energy storage medium that can be used in both sensible and latent forms of thermal energy storage units which solidifies in the presence of cooling resources but melts when the thermal energy is absorbed (Taghilou et al., 2016; Seifian et al., 2017a, 2017b). Bourdeau (1980) compared two passive storage collector walls using a phase change material (calcium chloride hexahydrate) with melting point of 29 °C and different thicknesses. He reported that an 8.1 cm of PCM wall possesses slightly better thermal performance compared with a 40 cm thickness of masonry wall. Silvia et al. (2002) have experimentally and numerically studied the dynamic thermal behavior of a latent heat thermal energy storage system with PCMs. To describe the performance of the storage, they used an enthalpy-based one-dimensional methodology. Tyagi and Buddh (2007) published a review for PCMs utilization in building’s components to reduce the temperature fluctuation and energy consumption. Castell et al. (2010) have experimentally analyzed a passive cooling method by utilizing PCM solar bricks in buildings. They reported that the PCM can decrease the peak temperature up to 1 °C and also reduce the electrical energy consumption about 15% which leads to 1–1.5 kg/year.m² reduction of the CO₂ emissions.

PCMs have been utilized in a wide range of applications considering their ability of storing and releasing a large amount of heat in the latent form at a roughly constant temperature. They are used in association with other energy technics such as PV modules, to increase their efficiency by moderating the temperature. As aforementioned, increasing the PV temperature reduces the efficiency. For instance, for crystalline silicon solar cells, the PV efficiency reduces with the rate of 0.4 °C/C14. Castell et al. (2010) have experimentally and numerically studied the dynamic thermal behavior of a latent heat thermal energy storage system with PCMs. To describe the performance of the storage, they used an enthalpy-based one-dimensional methodology. Tyagi and Buddh (2007) published a review for PCMs utilization in building’s components to reduce the temperature fluctuation and energy consumption. Castell et al. (2010) have experimentally analyzed a passive cooling method by utilizing PCM solar bricks in buildings. They reported that the PCM can decrease the peak temperature up to 1 °C and also reduce the electrical energy consumption about 15% which leads to 1–1.5 kg/year.m² reduction of the CO₂ emissions.

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Theoretical models are proposed and numerically solved by MAT-LAB for the PVT water collector system.

2. Problem definition

The schematic diagram of the PVT water collector with PCM and integrated electrolyzer is shown in Fig. 1a. This system consists of a photovoltaic and thermal system (PVT), a proton exchange membrane electrolyzer (PEM), a water tank, a DC water pump, a separator, and two product tanks. The present PVT system is a fully wetted absorber type PVT collector consisting of a frameless PV panel. Properties and design parameters of PV modules used in the system at their standard test conditions (I = 1000 W/m² and Tg = 25 °C) are presented in Tables 1 and 2. Fig. 1b depicts the detailed structure of the PVT collector with PCM. Due to the higher efficiency obtained using semitransparent or bi-glass PV module, this type of PV is selected in the present system. In this module, heat is transferred to the water from the back of the PV cells as well as the top surface of the blackened plate.

The surface area of the PVT collector is 6 m² connected to an insulated water tank with the capacity of 250 L, which can supply the hot water needed to meet employees demand at the filling station. In order to circulate the water in the system, a DC pump is used. To generate hydrogen using the electrical energy produced by the PV, the PEM type water electrolyzer is considered. Moreover, a separator is used to divide oxygen from water vapor generated in the electrolyzer. Produced hydrogen and oxygen gases are stored in two various tanks.

A fully wetted rectangular shaped channel collector is used referring its maximization ability of heat transfer area for water flow. Since one surface of the water channel is composed of the PV module, the heat is transferred directly to the flowing water from the back surface of the photovoltaic module. This direct heat transformation not only improves the system output thermal energy, but decreases the temperature difference between the photovoltaic cells and the coolant (water). Consequently, the
electrical efficiency and cooling effects are improved. The bottom and side surfaces of the PVT collectors are thermally isolated with 50 mm glass wool insulation and a space is also considered for PCM between the insulation and the absorber plate. Four various types of PCMs with different amounts of latent heat storage capacity are used to absorb or release the heat during the phase change process. The thermo-physical properties of utilized PCMs are given in Table 3.

The visible and ultraviolet parts of the solar spectrum are converted into electricity through PV cells, while the fully wetted absorber exploits infrared part of the solar spectrum as well as the excess heat of photovoltaic panel which is convectively transferred to the water. The system obtains the solar energy by two ways; direct gain, in which the solar radiation passes through the non-packing area, and convective heat transfer from the bottom of the PV module (indirect gain) (Gaur et al., 2017). A proportion of this thermal energy is stored as hot water inside the water tank and the rest is transferred to the PCM. When the wetted absorber channel has a higher temperature than the PCM’s, heat is reserved as sensible form, until the PCM’s melting point. Then, the PCM stores the heat within the phase changing in its latent form at a constant temperature, and when the whole PCM is melted, it stores the energy as sensible heat again. The PVT starts to cool down by diminishing the solar radiation; consequently, the melted PCM

---

Table 1
Properties of different utilized PV modules at STC.

<table>
<thead>
<tr>
<th>PV Type</th>
<th>C (J/kg K)</th>
<th>ρ (kg/m³)</th>
<th>η₀ (%)</th>
<th>β₀</th>
<th>β</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono-crystalline semitransparent PV</td>
<td>900</td>
<td>2702</td>
<td>18</td>
<td>0.006</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>Poly-Si (Acciani et al., 2010)</td>
<td>678</td>
<td>2320</td>
<td>11.6</td>
<td>0.004</td>
<td>0.83</td>
<td>0.9</td>
</tr>
</tbody>
</table>

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Fig. 1. a. The schematic diagram of the PVT system integrated with the PEM electrolyzer, b. the cross section of utilized PVT combined with PCM, c. the water flow over the PVT from x to x + dx.
unleashes the stored heat into the water until it solidifies. Supplying heat by the PCM and PV modules, extra heat can produce hot water even at night time.

In this study, a simple integrated PVT system with PCM is considered to produce water with a proton exchange membrane (PEM) electrolyzer from electricity generated by the PVT collector. The PEM conducts protons, electrically insulates the electrodes, and separates the produced gases. The produced electricity is transferred to the PEM electrolyzer in order to decompose water into oxygen and hydrogen. Generated hydrogen is combusted to produce electricity, and the excess water mixes with the vapor and oxygen is divided by the separator. The oxygen gas is directed to the PEM electrolyzer in order to decompose water even at night time.

3. Thermal modeling

The following assumptions are taken into account when applying the energy balance equations to each component of the present study can be given as follows:

3.1. Daytime modeling (The PVT system with the PCM)

During the sunshine hours, the energy balance equations for each item of the present study can be given as follows:

3.1.1. PV set

By considering the abovementioned assumptions, the energy balance for the photovoltaic set can be written as:

\[
m_{\text{PV}}C_{\text{PV}}\frac{dT_{\text{PV}}}{dt} = \left[k_{g}\alpha_{\text{PV}}\tau_{g}I(t) - h_{\text{PV→w}}(T_{\text{PV}} - T_{w}) - h_{\text{PV→sky}}(T_{\text{PV}} - T_{\text{sky}}) - h_{\text{PV→a}}(T_{\text{PV}} - T_{a})\right] \beta A_{\text{PV}}
\]

where, the left-hand side term presents the energy reserved in PV module. Whereas, the first term in the right-hand side indicates the rate of absorbed solar energy received by the photovoltaic panel, and the second term corresponds to the total heat transferred from solar cells of the PV set to the water through back glass. The next three terms represent the radiative heat losses from the PV to the sky, the convective heat losses from the PV to the ambient, and the convective heat losses to the blackened absorber plate respectively. The last item on the right-hand side of the equation expresses the electrical power produced by the PV module. In Eq. (1), \( \alpha_{\text{PV}}, \tau_{g}, \beta, \) and \( I(t) \) are absorptivity of the PV set, the transmissivity of the glass, packing factor and solar radiation, respectively (Table 2). In order to obtain actual thermal efficiency of the collector, the incident angle modifier \( (k_{g}) \) is considered and given in Table 4 depending on the angle of incident solar irradiance. In the present study, the incidence angle is calculated for the PVT collector facing south and tilted 40°. The incidence angle modifier is given by (Yousef et al., 2012) as:

\[
k_{g} = 1 - b_{0} \left( \frac{1}{\cos \theta} - 1 \right)
\]

where \( b_{0} \) is the incidence angle modifier coefficient with a positive constant value (Table 2) (Notton et al., 2005). Also, \( h_{\text{PV→w}} \) is the convective heat transfer coefficient from PV cells to the water through back glass and expressed as:

\[
h_{\text{PV→w}} = \left[ \frac{1}{h_{c,PV→w}^{-1} + \frac{l_{bg}}{K_{bg}}} \right]^{-1}
\]

where, \( l_{bg} \) and \( K_{bg} \) are back glass thickness and its conductivity respectively. Also:

\[
h_{c,PV→w} = \frac{K_{w}Nu}{D_{e}}
\]

where, \( K_{w} \) is the conductivity of water, \( Nu \) is the Nusselt number, and \( D_{e} \) is the equivalent diameter obtained for a noncircular channel by Eq. (5). For a constant heat flux and fully developed laminar flow within a rectangular shaped channel, \( Nu \) is calculated using Eq. (6),

<table>
<thead>
<tr>
<th>Table 2</th>
<th>The PVT system parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \text{PV} )</td>
<td>6 m² (2 × 3)</td>
</tr>
<tr>
<td>( a - b/a )</td>
<td>1 (0.01 m/0.01 m)</td>
</tr>
<tr>
<td>( b_{0} )</td>
<td>0.1</td>
</tr>
<tr>
<td>( \omega_{b} )</td>
<td>1</td>
</tr>
<tr>
<td>( T_{s} )</td>
<td>1</td>
</tr>
<tr>
<td>( L_{x} )</td>
<td>0.005 m</td>
</tr>
<tr>
<td>( K_{g} )</td>
<td>0.8 W/m·K</td>
</tr>
<tr>
<td>( L_{bg} )</td>
<td>0.005 m</td>
</tr>
<tr>
<td>( K_{bg} )</td>
<td>0.8 W/m·K</td>
</tr>
<tr>
<td>( L_{w} )</td>
<td>0.05 m</td>
</tr>
<tr>
<td>( K_{w} )</td>
<td>0.03 W/m·K</td>
</tr>
<tr>
<td>( C_{w} )</td>
<td>4190 J/kg·K</td>
</tr>
<tr>
<td>( m_{w} )</td>
<td>0.14 kg/s</td>
</tr>
<tr>
<td>( K_{w} )</td>
<td>0.6 W/m·K</td>
</tr>
<tr>
<td>( T_{0} )</td>
<td>25 °C</td>
</tr>
<tr>
<td>( T_{w,16 \text{Aug}} )</td>
<td>30.14 °C</td>
</tr>
<tr>
<td>( T_{w,14 \text{Mar}} )</td>
<td>9.73 °C</td>
</tr>
<tr>
<td>( h_{\text{eff}} )</td>
<td>1.85 W/(m²·K)</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>5.6697 × 10⁻⁸ W/(m²·K⁴)</td>
</tr>
<tr>
<td>Storage tank capacity</td>
<td>250 L</td>
</tr>
<tr>
<td>( U_{w,a} = \theta_{A_{\text{w}}} )</td>
<td>40 W/K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Thermo-physical properties of used PCMs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCM</td>
<td>( T_{m} ) (°C)</td>
</tr>
<tr>
<td>RT50 (Seidiyan et al., 2017b)</td>
<td>50</td>
</tr>
<tr>
<td>RT44 (Pakrouh et al., 2015)</td>
<td>41–44</td>
</tr>
<tr>
<td>RT35 (Taghilou et al., 2018)</td>
<td>35</td>
</tr>
<tr>
<td>RT28 (Taghilou et al., 2018)</td>
<td>28</td>
</tr>
</tbody>
</table>
proposed by Kays and Crawford (1980).

\[
D_e = \frac{4ab}{2(a + b)}
\]  

(5)

\[
Nu = 8.235 \left(1 - 1.893a + 3.76a^2 - 5.814a^3 + 5.361a^4 - 2a^5\right),
\]

\[
a = b/a
\]

(6)

where, \(a, a\) and \(b\) are aspect ratio, width and height of the water channel, respectively.

In Eq. (1), \(h_{PV}\) stands for the total heat transfer coefficient from the photovoltaic module to the sky and is obtained by:

\[
h_{PV,sky} = \left[\frac{1}{h_r, PV, sky} + \frac{a}{K_s}\right]^{-1}
\]

(7)

According to (Chaabane et al., 2014), \(h_r, PV, sky\) is defined as follow:

\[
h_{r, PV, sky} = \varepsilon PV, APV \frac{T_{PV}^4 - T_{sky}^4}{T_{PV} - T_{sky}}
\]

(8)

here, \(\varepsilon\) is Stefan Boltzmann constant, \(\varepsilon_{PV}, APV\) and \(T_{PV}\) are effective emissivity, surface area and temperature of the PV set, sequentially. \(T_{sky}\) is the sky temperature which is defined as follows (Zurigat and Abu-Arabi, 2004):

\[
T_{sky} = T_\infty - 6
\]

(9)

Also:

\[
h_{PV, a} = \left[\frac{1}{h_{c, PV, a}} + \frac{K_s}{L_s}\right]^{-1}
\]

(10)

\[
h_{c, PV, a} = 2.8 + 3 v
\]

(11)

where \(v\) is wind velocity (Table 4).

Heat conduction coefficient transferred from photovoltaic set to the absorber channel is equal to the total heat transfer coefficient from the photovoltaic to the water obtained by Eq. (2) (Gaur et al., 2017). Accordingly:

\[
h_{PV\rightarrow ab} = h_{PV\rightarrow w}
\]

(12)

Finally, depending on the PV temperature, \(\eta_{PV}\) is defined as the electrical efficiency of the photovoltaic panel and calculated as (Skoplaki and Palyvos, 2009):

\[
\eta_{PV} = \eta_0 [1 - \beta_0 (T_{PV} - T_0)]
\]

(13)

where \(T_0\) is standard test condition (STC) temperature and equals to 25 °C. Also, \(\eta_0\) and \(\beta_0\) given in Table 1 for utilized PV modules are the electrical efficiency and the temperature coefficient of the photovoltaic set, respectively.

3.1.2. Fully wetted absorber channel

Similar to the PV module, energy balance for the fully wetted absorber channel can be written as:

\[
k_b \varepsilon_{ab} \frac{T_g (1 - \beta) I(t) \Delta A_{ab}}{h_{ab\rightarrow w}(T_{ab} - T_w)A_{ab} + h_{ab\rightarrow PCM}(T_{ab} - T_{PCM})A_{ab}} = h_{ab\rightarrow ab}(T_{ab} - T_a)A_{ab}
\]

(14)

The left-hand side indicates the energy absorbed by the blackened absorber plate through the non-packing area of the photovoltaic panel and the heat obtained from the cells by the back glass. While, the right-hand side presents the heat transferred from the blackened absorber plate to the PCM and water via conduction and convection mechanisms, respectively. In Eq. (14), \(A_{ab}\) and \(a_{ab}\) are the surface area and absorptivity of the absorber plate respectively. In addition, \(h_{ab\rightarrow ab}\) is conduction heat transfer coefficient from the PV to the absorber channel calculated from Eq. (12), \(h_{ab\rightarrow w}\), and \(h_{ab\rightarrow PCM}\).
are respectively heat transfer coefficients from the absorber channel to the water and PCM. Heat transfer coefficient from the absorber channel to the water is equal to that from photovoltaic cells to the water determined by Eq. (2) (Gaur et al., 2017). So:

\[ h_{ab-w} = h_{PV-w} \]  \hspace{1cm} (15)  

\[ h_{ab-PCM} \]  can be calculated as:

\[ h_{ab-PCM} = \left[ \frac{h_{PCM}}{K_{PCM}} \right]^{-1} \]  \hspace{1cm} (16)

where \( h_{PCM} \) and \( K_{PCM} \) are the thickness and conductivity of the PCM, respectively (Table 2).

3.1.3. Water inside the fully wetted absorber channel

Considering Fig. 1c, the amount of heat transferred to the water while it moves from \( x = 0 \) to \( x = dx \) can be written as below:

\[ q_w = \frac{Q_w}{w} \frac{dx}{dx} = m_w C_w \frac{dT_w}{dx} \]  \hspace{1cm} (17)

In which \( C_w, m_w, dT_w \) and \( w \) are heat capacity, the mass flow rate, the temperature gradient of water and the width of the photovoltaic thermal unit, respectively. The term \( q_w \) represents the heat transferred to the water per area at the distance of \( x \) from the inlet edge of the PVT collector.

For the cross-sectional area of \( w \times dx \), energy balance for the water inside the absorber channel will be:

\[ h_{PV-w}(T_{PV} - T_w) w \ dx + h_{ab-w}(T_{ab} - T_w)w \ dx = m_w C_w \frac{dT_w}{dx} dx \]  \hspace{1cm} (18)

Left-hand side of Eq. (18) indicates the total heat transferred to the water via the PV module and the absorber channel. While, the right-hand side is the rate of heat received by the water passing through the absorber channel. Apparently, the average temperature of water is found by integrating the \( T_w \) from \( x = 0 \) to \( x = L \).

3.1.4. Phase change material (PCM)

Energy balance equations for PCM results in:

\[ h_{ab-PCM}(T_{ab} - T_{PCM})A_{ab} = M \frac{dT_{PCM}}{dt} + U_{PCM-a} (T_{PCM} - T_a)A_{PCM} \]  \hspace{1cm} (19)

\[ M = \left\{ \begin{array}{ll} m_1 C_1, & \text{for } T_{PCM} < T_m \\ m_2 C_2, & \text{for } T_{PCM} = T_m \\ m_3 C_3, & \text{for } T_{PCM} > T_m \end{array} \right. \]  \hspace{1cm} (20)

\[ U_{PCM-a} = \left[ \frac{1}{h_i} + \frac{L_{in}}{K_{in}} \right]^{-1} \]  \hspace{1cm} (21)

The left-hand side of Eq. (19) shows the heat received by the PCM from the absorber channel. The right-hand side consists of two terms representing the thermal energy reserved in the PCM and the PCM overall heat losses of to the ambient, respectively. The term \( h_i \) in Eq. (21), is the ambient convective heat transfer coefficient.

Using the separation of variables method to solve Eqs. (1), (18) and (19) analytically, the PV module, water and PCM temperatures can be calculated (Gaur et al., 2017):

\[ T_{PV} = \frac{f_1(t)}{a_1} \left( 1 - e^{-\frac{a_1}{t}} \right) + T_{PV,0} e^{-\frac{a_1}{t}} \]  \hspace{1cm} (22a)

\[ T_w = \frac{f_2(t)}{a_2} \left( 1 - e^{-\frac{a_2}{t}} \right) + T_{PV,0} e^{-\frac{a_2}{t}} \]  \hspace{1cm} (22b)

\[ T_{PCM} = \frac{f_3(t)}{a_3} \left( 1 - e^{-\frac{a_3}{t}} \right) + T_{PCM,0} e^{-\frac{a_3}{t}} \]  \hspace{1cm} (22c)

here, \( T_{PV,0}, T_{w,0} \), and \( T_{PCM,0} \) are the initial values of the PV module, water, and the PCM temperatures. \( f_i(t) \) is the average value of \( f_i(t) \), which depends on the ambient and sky temperatures, heat transfer coefficients, and solar radiation that can be considered constant at the time interval of \( dt \). \( f_i(t) \) is presented in the Appendix along with \( a_i \). Finally, the absorber channel’s temperature is calculated by Eq. (19).

3.2. Nighttime modeling (The PVT collector with the PCM)

3.2.1. Phase change material (PCM)

In this mode, PCM will be the only source of energy. Applying the first law of thermodynamics to the PCM results in:

\[ M \frac{dT_{PCM}}{dt} + U_{PCM-a} (T_{PCM} - T_a)A_{PCM} + h_{PCM-ab}(T_{PCM} - T_{ab})A_{ab} \]  \hspace{1cm} (23a)

for \( T_{PCM} \neq T_m \)

\[ M \frac{dT_{PCM}}{dt} = U_{PCM-a} (T_{PCM} - T_a)A_{PCM} + h_{PCM-ab}(T_{PCM} - T_{ab})A_{ab} \]  \hspace{1cm} (23b)

where \( M \) is calculated using Eq. (20). The left-hand side of Eqs. (23a) and (23b) stands for the latent and sensible heat saved in the PCM, respectively. The right-hand sides of these equations show the total heat loss to the ambient and heat transfer to the absorber channel. The heat is transferred by free convection mechanism from melted PCM to the absorber channel, therefore, the heat transfer rate in terms of the Nusselt number is defined as (Dubey and Tiwari, 2009):

\[ Nu = 0.133 Ra^{0.326} \frac{0.0686}{(1/T_{PCM})} \]  \hspace{1cm} (24)

where \( Ra = Gr \times Pr \). In which \( Gr, Pr \) and \( Ra \) are Grashof, Prandtl and Rayleigh numbers, respectively. Moreover, \( T_{PCM} \) is the PCM thickness and \( l \) is the absorber channel’s length.

3.2.2. Fully wetted absorbing channel and water

Similar to the daytime mode, energy balance for the absorber channel and water can be written as:

\[ h_{PCM-ab}(T_{PCM} - T_{ab})w \ dx = h_{ab-w}(T_{ab} - T_w)w \ dx + h_{PV-ab}(T_{PV} - T_w)w \ dx \]  \hspace{1cm} (25a)

\[ h_{ab-w}(T_{ab} - T_w)w \ dx = m_w C_w \frac{dT_w}{dx} dx + h_{PV-w}(T_{PV} - T_w)w \ dx \]  \hspace{1cm} (25b)

The left-hand side of Eq. (25a) shows the heat transfer from PCM to the absorber channel, while the right-hand side shows the energy transferred from the absorber channel to the water and PV
module, respectively. The left-hand side of Eq. (25b) represents the heat transferred to the water from the absorber channel and the right-hand side demonstrates the energy stored in the water and heat transfer to the PV panel.

3.2.3. PV module

During the off-sunshine hours, the energy balance for the PV module is written as:

\[
h_{\text{abs} - \text{PV}}(T_{\text{ab}} - T_{\text{PV}})A_{\text{PV}} = m_{\text{PV}}C_{\text{PV}} \frac{dT_{\text{PV}}}{dt} + h_{\text{PV} - \text{sky}}(T_{\text{PV}} - T_{\text{sky}})A_{\text{PV}} + h_{\text{PV} - \text{a}}(T_{\text{PV}} - T_{\text{a}})A_{\text{PV}}
\]

(26)

The left-hand side of Eq. (26) is the amount of heat transferred from the absorber channel to the PV module which equals to the heat stored by the PV module and also heat loss to the sky and ambient.

Eqs. (23) and (26) can be analytically solved by using separation of variables method (Gaur et al., 2017):

\[
T_{\text{PCM}} = \frac{f_4(t)}{a_4}(1 - e^{-a_4 t}) + T_{\text{PCM0}}e^{-a_4 t}
\]

(27)

\[
T_{\text{PV}} = \frac{f_5(t)}{a_5}(1 - e^{-a_5 t}) + T_{\text{PV0}}e^{-a_5 t}
\]

(28)

\[T_{\text{ab}} \text{ and } T_{\text{w}} \text{ can be obtained by rewriting Eqs. (25a) and (25b)}.\]

3.3. PVT system without PCM

3.3.1. Wetted absorber channel

For PV module and water, the heat balance is similar to Eqs. (1) and (18). However, it is different for the absorber channel written as:

\[
k_{\text{ab}} \alpha_{\text{ab}} \tau_{\text{G}}(1 - \beta)I(t)A_{\text{ab}} + h_{\text{abs} - \text{ab}}(T_{\text{ab}} - T_{\text{w}})A_{\text{ab}}
\]

\[= h_{\text{abs} - \text{w}}(T_{\text{ab}} - T_{\text{w}})A_{\text{ab}} + U_{\text{ab} - \text{a}}(T_{\text{ab}} - T_{\text{a}})A_{\text{ab}}\]

(29)

where:

\[U_{\text{ab} - \text{a}} = \frac{1}{\frac{1}{h_1} + \frac{1}{K_{\text{in}}}}^{-1}\]

(30)

Similar methods are used to solve these equations to find the water and PV module temperatures. Therefore, \(T_{\text{ab}}\) is calculated by rewriting Eq. (29).

3.4. Water storage tank

For the studied PVT system, a stratified water storage tank is chosen utilizing one dimensional module for the temperature gradient. The tank is assumed to consist of \(N_n\) fully mixed equal volume segments dividing the tank along its vertical axis, where \(n = 1\) and \(n = N_n\) represent the bottom and the top segments, respectively. Considering the study done by Hobbi and Siddiqui (2009), the water storage tank is divided into 6 nodes (\(N_n = 6\)). In the present work, the water heated by the PV enters the tank via a port at \(N_n = 6\) (top of the tank), while the cold water leaves the bottom of the tank (\(N_n = 1\)). Furthermore, the makeup water enters the tank at \(N_n = 1\). The temperature of makeup water is obtained (Table 2) using the equation proposed by Jamshidi and Mosaffa (2018), for the depth of 1.5 m below the surface which is more than the freezing depth of water pipe for Shiraz. Each node temperature in of the tank is obtained using the energy balance as follows (Herrando et al., 2018):

\[
T_{\text{tank},n}(i + 1) = T_{\text{tank},n}(i) + \frac{Q_{\text{water},n}(i) + Q_{\text{cond},n}(i) + Q_{\text{loss},n}(i)}{m_{t,\text{n}}C_w}\Delta t
\]

(31)

where \(T_{\text{tank},n}(i + 1), T_{\text{tank},n}(i), m_{t,\text{n}}\) and \(\Delta t\) are the tank temperatures at segment \(n\) at time steps \(i + 1\) and \(i\), water mass in each tank node and the time step size, respectively. Here, \(Q_{\text{water},n}(i), Q_{\text{cond},n}(i)\) and \(Q_{\text{loss},n}(i)\) represent the heat fluxes corresponding to the water flow, conduction between the tank nodes and heat loss in the given order which are expressed as (Herrando et al., 2018):

\[
Q_{\text{water},n}(i) = \sum m_{\text{w,in},n}C_w(T_{\text{w,in},n}(i) - \sum m_{\text{w,out},n}C_wT_{\text{w,out},n}(i))
\]

(32a)

\[
Q_{\text{cond},n}(i) = \frac{\lambda_{\text{eff}}A_{\text{tank}}}{H_{\text{tank},n}}(T_{\text{tank},n + 1}(i) + T_{\text{tank},n - 1}(i) - 2T_{\text{tank},n}(i))
\]

(32b)

\[
Q_{\text{loss},n}(i) = U_{\text{tank} - \text{a}}A_{\text{tank}}(T_{\text{a}}(i) - T_{\text{tank},n}(i))
\]

(32c)

where \(m_{\text{w,in},n}, m_{\text{w,out},n}, T_{\text{w,in},n}(i)\) and \(T_{\text{w,out},n}(i)\) demonstrate the input and output mass flow rate of water and their temperatures at time step \(i\) for segment \(n\), respectively. In addition, \(A_{\text{tank}}, A_{\text{tank},n}\) and \(H_{\text{tank},n}\) are side surface area, cross section area and height of the node in the given order. In Eq. (32b), \(\lambda_{\text{eff}}\) is the effective vertical thermal conductivity which takes into account the conduction of water, tank walls and the internal components and is equal to 1.85 \(W/mK\) (Crucifixshank and Harrison, 2010).

In the case without PCM, there is no water circulation in the PVT collector during the night. Therefore, the energy balance is expressed as:

\[
T_{\text{tank},n}(i + 1) = T_{\text{tank},n}(i) + \frac{Q_{\text{cond},n}(i) + Q_{\text{loss},n}(i)}{m_{t,\text{n}}C_w}\Delta t
\]

(33)

In order to show the variation of water storage tank temperature, the average of all segments’ temperatures is considered in section 5.

3.5. The electrolyzer

The PEM type water electrolyzer integrated with the PVT system is considered to produce hydrogen using the electrical energy generated by the PV set. Water splits into oxygen and hydrogen as following chemical reaction (Akrami et al., 2018):

\[
H_2O \rightarrow H_2 + 1/2 O_2, \quad \Delta H = 285.84 \text{kJ}
\]

(34)

where \(\Delta H\) is the splitting reaction enthalpy of water. The PEM efficiency is considered to be a constant amount of 61.37% (Cilogullari et al., 2017).

3.6. Overall electrical and thermal energy and exergy analysis

The total input energy to the PVT unit is given as (Cilogullari et al., 2017):

\[
E_{\text{in}}(t) = A_{\text{PV}} I(t)
\]

(35)

The total output energy \(E_{\text{out}}\) consists of electricity and thermal energy that can be given as:
\[ E_{\text{out}} = E_{\text{el}} + E_{\text{th}} \tag{36} \]

For the present system, the overall daily electrical energy is:

\[ E_{\text{el}} = E_{\text{el, daily}} - P_{\text{pump}} \tag{37} \]

here, the first term on the right-hand side is daily electrical energy production and the second term shows the power utilized by the DC pump to supply the pressure losses during the operation and circulate the water (Gaur et al., 2017). The instantaneous output electrical power of the PVT system is defined as (Mazraeh et al., 2018):

\[ E_{\text{el}}(t) = \eta_{PV} \beta A_{PV} T_{B} I_{S}(t) \tag{38} \]

The output thermal power can be calculated as:

\[ E_{\text{th}} = Q_{\text{PCM}} + M_{\text{tank}} C_{w} (T_{w, o} - T_{w, i}) \tag{39a} \]

\[ Q_{\text{PCM}} = m_{\text{PCM}} C_{\text{PCM}} 4T_{\text{PCM}} + I_{\text{PCM}} A_{\text{PCM}} \tag{39b} \]

where \( Q_{\text{PCM}} \) is the energy stored at the PCM (for the system without PCM, \( Q_{\text{PCM}} = 0 \)). The received heat is obtained by Eq. (39a) during the daytime. Regarding the nighttime non-circulated water, \( T_{w, o} - T_{w, i} \) is replaced by the difference between initial and last temperatures of the tank water.

For the present PVT water collector system, the daily electrical and thermal energy efficiencies are calculated as follows (Gaur et al., 2017):

\[ \eta_{\text{el, daily}} = \frac{\sum_{24 \text{ hours}} E_{\text{el}}}{A_{\text{PV}} T_{B} \sum_{24 \text{ hours}} I_{S}(t)} \tag{40} \]

\[ \eta_{\text{th, daily}} = \frac{\sum_{24 \text{ hours}} E_{\text{th}}}{A_{\text{PV}} T_{B} \sum_{24 \text{ hours}} I_{S}(t)} \tag{41} \]

For the total input exergy, Eq. (42) is used:

\[ E_{\text{in}}(t) = A_{\text{PV}} I_{\text{ex}}(t) \tag{42} \]

where \( E_{\text{in}} \) is the exergy of the solar radiation reached on the system surface. The Petela’s equation is considered for \( I_{\text{ex}}(t) \) (Petela, 2003):

\[ I_{\text{ex}}(t) = I(t) \times \left( 1 - \frac{4}{3} \frac{T_{0}}{T_{s}} + \frac{1}{3} \frac{T_{0}}{T_{s}} \right)^{4} \tag{43} \]

\( T_{s} \) is the solar radiation temperature which is equal to the temperature of the sun (6000 K) (Mazraeh et al., 2018). Then:

\[ I_{\text{ex}}(t) = 0.933 I(t) \tag{44} \]

The total output exergy (\( E_{\text{out}} \)) consists of electricity and thermal exergy is written as:

\[ E_{\text{out}} = E_{\text{el}} + E_{\text{th}} \tag{45} \]

The instantaneous output electrical exergy of PVT unit is given as (Mazraeh et al., 2018):

\[ E_{\text{ex, el}}(t) = \eta_{PV} A_{PV} I_{\text{ex}}(t) \tag{46} \]

While the output thermal exergy can be obtained by (Cilogullari et al., 2017):

\[ E_{\text{ex, th}}(t) = \left( 1 - \frac{T_{w}}{T_{PV}} \right) \times E_{\text{th}}(t) \tag{47} \]

The exergy efficiency of the PVT set can be calculated as the ratio of the output to the input exergy (electrical and thermal) and given as:

\[ \eta_{\text{ex, el}} = \frac{E_{\text{ex, el}}}{E_{\text{in}}} \tag{48a} \]

\[ \eta_{\text{ex, th}} = \frac{E_{\text{ex, th}}}{E_{\text{in}}} \tag{48b} \]

4. Numerical analysis

Numerical solving methods in MATLAB are used to couple and solve above-mentioned equations. Fig. 2 shows the calculation steps of utilized numerical methods. A computer code is developed to calculate the equations obtained from energy and exergy balance for the present PVT water collector system for various PCMs and PV modules. The program is run for the period of 24 h with the time step of 0.1 s. The initial temperature of PVT, PCM, absorber channel, and water are considered to be equal to the ambient temperature at \( T_{0} \), when the sun rises and the solar radiation becomes available. Since the pipes are well-insulated, the PV inlet water temperature for the next step is considered to be equal to the water temperature of the lowest node of the storage tank. When the sun sets, the program for the discharge mode starts and the PCM operates as the heat source. After solving all equations for 24 h, the system electrical and thermal efficiencies are determined.

5. Results and discussions

Hourly average solar radiation and ambient temperature for typical winter and summer days on March 14 and August 16, 2018, Shiraz, Iran (given in Table 4) as well as the monthly average data for 2017 (Table 5) are utilized (Cedar Lake Ventures Inc, 2018; Fars Province Meteorolog). Using MATLAB data processing program, equations are solved to determine the values of \( T_{PV}, T_{aw}, T_{w}, T_{PCM}, T_{fl}, \eta_{PV}, \eta_{PV}, \) output thermal and electrical energies and exergies along with the hydrogen production rate.

5.1. Methodology verification

In order to assess the validity of the methodology used in the current work, numerical data reported by Gaur et al. (2017) are utilized. All parameters, such as PCM and PV module types are selected the same as the parameters used by Gaur et al. (2017). Fig. 3a and b depict the temperatures of PV and water storage tank, and PV module efficiency of the PVT system with PCM for 8 July, Lyon, France, respectively. Referring to Fig. 3a and b, the data obtained by the present methodology are in fair agreement with those given by Gaur et al. (2017).

5.2. Water mass flow rate

The cooling water mass flow rate as an effective parameter of the system performance must be determined accurately since it regulates the PV temperature. Fig. 4 demonstrates the variation of the mean water storage tank temperature and PV module efficiency for different water mass flow rates for Aug 16 at 8:00 a.m. and 11:00 a.m. The mean tank temperature (for 11:00 a.m.) rises when the water mass flow rate increases until it reaches a constant value of 60.5 °C. The PV module efficiency (for 8:00 a.m.) is constant at the beginning and rises when the water flow rate reaches to an amount of 0.20 kg/s. However, it does not change for 11:00 a.m. Considering Fig. 4, increasing the mass flow rate of water after a certain amount
would not be beneficial. Therefore, the water mass flow rate of 0.14 kg/s is determined for all cases studied in this paper.

5.3. Component temperatures and PV efficiency

Fig. 5a and b depict hourly variations of the PV, absorber channel, water, PCM, and mean storage tank temperatures as well as the PV module efficiency with and without PCM for Mar 14 and Aug 16, respectively. Referring to Fig. 5a and b, the temperatures of the PV, absorber channel, water, PCM and storage tank are predominantly dependent on the strength of solar radiation. For the system with PCM, $T_{PV}$, $T_{ab}$, $T_w$ and $T_{tank}$ have a maximum value at a specific solar radiation intensity. Moreover, the downward trend for $T_{PV}$, $T_{ab}$, $T_w$ and $T_{tank}$ continues with a more subtle slope even after sunset for both winter and summer days within the nighttime. The PCM temperature in the summer, however, increases by the solar radiation intensity to its melting point and remains constant until 2:00 a.m. and then decreases. This gentle reduction rises from the heat released by the PCM set during its solidification process. The maximum values of $T_{PV}$, $T_{ab}$, $T_w$, $T_{PCM}$ and $T_{tank}$ for the case with PCM are 34.99, 35.32, 35.15, 33.72 and 32.26 °C for Mar 14, and 62.35, 61.86, 62.10, 44.00 and 57.97 °C for Aug 16, respectively. It is obvious that the PV, absorber channel, and water temperatures are almost the same. The low temperature difference between PV, water and absorber channel is due to direct connection between them. The temperature of PCM is lower than that of the PV at the beginning. Therefore, it increases as solar intensity rises because of the heat transfer from the absorber channel via conduction. For Aug 16, the PCM temperature reaches its melting temperature at 9:00 a.m. and stays at the same level even for off-sunshine hours (until 2:00 a.m.). During the discharging process, the PCM module starts to solidify and acts as the PVT system heat source with a higher temperature than the PV panel for both winter and summer days.

Eventually, when the PCM completely solidifies in summer, its temperature falls down as time elapses. In the absence of solar radiation and when the ambient temperature decreases during the night time, the mean storage tank temperature reduces. For Aug 16, the tank temperature reduction is lower for the PVT system with PCM than that for the systems without PCM arising from the energy release during the discharging process. On the other hand, for Mar 14, the PCM temperature increases as the solar radiation intensifies. However, referring to the lower ambient temperature and solar radiation compared to those in Aug 16, the PCM temperature does not reach the melting point. Therefore, the PCM does not reserve considerable amount of energy to be released during the night. Moreover, regarding the absence of water circulation in the PVT system without PCM during off-sunshine hours, the mean tank temperature for the case without PCM is higher than the mean tank temperature for the PVT system with PCM in winter.

Fig. 5a and b also show the changes in the PV efficiency ($\eta_{PV}$) during the sunshine hours. Considering Eq. (13), the PV module efficiency has an inverse relationship with its temperature. Therefore, as the PV temperature increases at the beginning hours of the day, the efficiency of PV module falls. However, after noon, when the solar radiation intensity and consequently the PV temperature decrease as time elapses, the PV module efficiency rises. The minimum PV module efficiency with the PCM set is obtained 16.90% for Mar 14 and 13.95% for Aug 16 at 12:00 p.m.

5.4. Effects of PCM

Difference between the presence and absence of the PCM can be drawn from Fig. 5a and b. The PV, absorber channel, water, and average storage tank temperatures are higher than those for the case without the PCM for Aug 16. In contrast, these temperatures
are almost the same as the case with and without PCM for Mar 14, since the PCM does not reach its melting point during the winter (due to lower solar radiation and ambient temperature). As the PCM absorbs heat during the sunshine hours, it reserves a proportion of solar radiant energy and comparatively lower amount of energy is gained by the PV module. Consequently, the PV temperature for the case with PCM is lower than that without it. Lower PV temperature lessens the temperatures of absorber, water, and mean tank as well, however, it increases the PV set efficiency. The maximum temperatures of the PV, absorber channel, water, and mean tank for Aug 16 are recorded 62.35, 61.86, 62.10 and 57.97 °C for the case with PCM and 70.22, 70.83, 70.52 and 65.14 °C for the case without PCM, in the given order. As aforementioned, the presence of the PCM leads to a lower PV temperature in summer which increases the PV efficiency (from 13.10 to 13.95% at its lowest amount). Accordingly, the presence of the PCM improves the performance of this system by saving energy during sunshine hours and releasing it during the nighttime. However, it is noteworthy to say that the presence of PCM does not have a significant effect on the PV efficiency for Mar 14 since the PCM does not reach its
melting point.

Fig. 6a and b depict the effects of the type of the PCM on the temperatures of PV and PCM as well as \( \eta_{PV} \). Two main parameters affecting these figures are the melting temperature and latent heat capacity of PCMs. RT50 has a higher melting point and therefore leads to higher PV temperature and lower PV efficiency compared to RT44. On the other hand, RT44 has a higher latent heat capacity, therefore, reserves more amounts of energy and remains at its melting point for a long time. As it is demonstrated in Fig. 6a, RT50 stays at its melting point until 21:00, nevertheless, the RT44 remains at the melting point until 2:00 a.m. which confirms that RT44 saves more amounts of energy in the latent form comparing to RT50. Since the RT35 has the minimum melting point and latent heat capacity, it starts melting sooner (which is completely melted at 14:00). When the PCM is totally melted, its temperature increases significantly representing the PCM capability to save energy in the sensible point. Moreover, referring to Fig. 6a and b, PV temperature is the highest for the system without PCM which eventually leads to the lowest PV efficiency.

Fig. 7a and b make a comparison between the temperatures of PV, water, and PCM as well as the PV module efficiency for various PCM masses (120, 80, 40 and 20 kg). Referring to Fig. 7a and b, by increasing the mass of PCM, the PV water temperatures rise during sunshine hours. However, they decrease during the night since the PCM acts as a heat sink within the day, and heat source during the night. Therefore, it respectively saves and releases lower amounts of energy during sunshine and off-sunshine hours by a reduction in mass. For 120 kg of PCM at melting state point, the PCM fails to melt completely and remains at this temperature until 2:00 a.m. However, PCM with lower weight begins to melt sooner and reaches to relatively higher temperature after completely melting since the input energy is the same for all cases. Furthermore, since the PV temperature inversely affects the efficiency, the low weighted PCMs with higher PV temperatures lead to lower PV efficiencies. Interestingly, the PV temperature for 120 kg of PCM is higher than that for 80 kg demonstrating an optimum value for PCM mass. The PCM mass is in direct relation with its thickness, and \( I_{PCM} \) increases by its mass. Since, increasing the thickness of PCM leads to a rise in its thermal resistance, increasing the PCM mass from 80 to 120 kg decreases the performance of the proposed system.

5.5. Effects of PV type

In order to examine the effects of the PV type on the system performance, Fig. 8 represents the PV module efficiency for two different PV types with and without the PCM at different time intervals. Fig. 8 confirms the overall behavior of the PV efficiency, which falls as solar radiation intensifies. Expectedly, for both PV types, the efficiency for the case with PCM is higher than that of without PCM due to the effects of PCM on the PV temperature. Furthermore, the PV module efficiency for the Mono-Crystalline Semitransparent PV type is higher than the efficiency of Poly-Si PV type, since \( \eta_0 \) i.e. the main factor influencing the PV module efficiency, is 18% for mono-crystalline PV, while it is 11.6% for Poly-Si PV (Table 1).

5.6. Electrical and thermal energy analysis

Hourly variations of output electrical and thermal energies during the day with and without PCM for Mar 14 and Aug 16 are illustrated in Fig. 9a and b, respectively. Fig. 9a shows that the electricity generation grows by increasing the input solar radiation intensity for all cases. According to Eq. (38), the generated electrical energy not only depends on the intensity of solar radiation but also is a function of \( \eta_{PV} \). Therefore, owing to the fact that the PVT system without PCM has lower \( \eta_{PV} \) in comparison to that with PCM, lower amounts of electricity production for the cases without the PCM can be explained. Moreover, Fig. 9a shows that electricity production during the summer is higher than that during the winter as a result of limited sunshine hours and lower solar radiation intensity. Maximum output electricity for Mar 14 and Aug 16 with and without the PCM are calculated as 0.582, 0.580, 0.679 and 0.639 kWh, respectively. According to Fig. 9b, the daily output thermal energy for the PVT system with PCM is higher than that of system without PCM, considering the PCM capability of storing higher amounts of thermal energy. For off-sunshine hours, the thermal energy amount for the PVT system without PCM is equal to zero due to the lack of water circulation. However, for the system with PCM, owing to the heat loss from PCM, output thermal energy is negative. In general, the thermal energy for summer is higher than that for winter because the solar radiant intensity and ambient temperature are higher. Maximum thermal energy for Mar 14 and Aug 16 with and without the PCM are obtained as 1.03, 0.77, 1.83...
and 1.35 kWh respectively.

Fig. 10a and b compare electrical and thermal efficiencies of the current PVT system with and without PCM for the investigated winter and summer days. As depicted in Fig. 10a, electrical efficiency has a similar trend with $h_{PV}$. Furthermore, the efficiency for Mar 14 is higher than that for Aug 16, because the ambient temperature as well as the solar radiation are lower during the winter time, and consequently the PV temperature is lower. The minimum electrical efficiencies for the systems with and without PCM, are 15.20 and 15.13% respectively for Mar 14 occur at around 12:00. Furthermore, the corresponding values are obtained for Aug 16 at 13:00 as 12.53 and 11.76% respectively. The PVT system thermal efficiency increases sharply at earlier hours of the day since the output energy changes significantly during this period of time. Then the thermal efficiency remains steady until it decreases suddenly during the last sunshine hours. This considerable reduction is rooted in the sharp decline of the solar radiation while the output thermal energy does not experience substantial change during these hours. In addition, due to the higher amount of thermal energy providing by PCM, the system thermal efficiency is higher than that of the system without PCM. Thermal efficiencies of the current system, with and without PCM, for winter and summer at 13:00 are determined as 13.79, 16.75, 30.13 and 22.24%, in the given order.

### 5.7. Electrical and thermal exergy analysis

Hourly variations of output electrical exergy during sunshine hours with and without PCM for Mar 14 and Aug 16 are presented in Fig. 11a. Similar to the electrical energy, the electrical exergy rises to a peak related to the maximum solar radiation intensity, then starts to reduce. Maximum electrical exergies for the system with and without PCM are respectively 0.543 and 0.541 kWh for winter and 0.633 and 0.596 kWh for summer. As expected, the electrical exergy is higher for the PVT system with PCM, due to the PV efficiency which is higher in the presence of the PCM. Since the solar radiation intensity is lower during the winter day, the electrical exergy for winter is less than summer. Fig. 11b depicts the output thermal exergy with and without PCM for typical summer and winter days. The overall trend of this graph is almost similar to the output thermal energy (Fig. 9b). Likewise, the output thermal exergy for the system with PCM is higher than that for the system without PCM for almost whole day. Moreover, the output thermal exergy for summer is higher than winter, as expected. The maximum thermal exergies of the system with and without 120 kg of RT44 are 0.059 and 0.051 kWh for Mar 14 and 0.152 and 0.141 kWh for Aug 16, respectively.

Fig. 12a and b demonstrate the hourly variations of electrical and thermal exergy efficiencies for the systems with and without PCM for Mar 14 and Aug 16 subsequently. The electrical exergy efficiency behaves like electrical energy efficiency. The electrical exergy efficiency for the PVT system with PCM is higher than that for the system without it, and it is higher for winter than summer. Fig. 12b reveals that, for Aug 16, thermal exergy efficiencies considerably change by time in comparison with Mar 14. The irregularities at the beginning and end of the sunshine hours result from dramatic changes in solar radiation during these periods of time. The output thermal exergy is higher at the presence of PCM since the input exergy is the same for both systems (see Fig. 11b). Therefore, the thermal exergy efficiency for the PVT system with the PCM is higher than the case without it.
Fig. 9. Variation of a. Electrical and b. Thermal energies during the day with and without PCM for 14 Mar and 16 Aug.

Fig. 10. Hourly variation of a. Electrical and b. Thermal efficiencies during the day with and without PCM for 14 Mar. and 16 Aug.

Fig. 11. Variation of a. Electrical and b. Thermal exergies during the day with and without PCM for 14 Mar. and 16 Aug.
5.8. Hydrogen production

In order to show the hydrogen production capacity of the proposed unit, Fig. 13 is plotted. Since the PEM water electrolyzer utilizes all generated electricity to decompose the water, the hydrogen production is in direct relation with generated electricity and solar radiation intensity. Therefore, the hydrogen production increases by the intensity rise of solar radiation until it reaches a peak (10.50 gr/hr at 13:00 for summer with Mono-Crystalline Semitransparent PV and 120 kg of RT44) and then starts to decline gradually. As the solar radiation intensity is high in summer, the produced hydrogen for the summertime is higher than that for winter. Furthermore, due to the lower values of the PV temperature for the system with PCM and consequently higher values of the electricity generation and $P_{PV}$, the hydrogen production for the PVT system with the PCM is higher than the system without PCM. However, since the PCM does not pass into its latent form due to the lower solar radiation and ambient temperature during the winter, the hydrogen production for Mar 14 is almost the same for the PVT system with and without PCM. The maximum hourly hydrogen production of the PVT system with and without PCM are 9.00 and 8.96 gr for Mar 14 and 10.50 and 9.88 gr for Aug 16 at 12:00 p.m.

Output monthly electrical energy and exergy for the proposed PVT unit are depicted in Fig. 14a for the whole 2017. As the mean daily solar radiation increases, the electrical energy and exergy rates rise and reach their maximum amounts of 193.20 and 180.26 kWh in June, when the mean daily solar radiation is 26.8 MJ/m². For the whole year, the output exergy is lower than the output energy, as expected. Furthermore, Fig. 14b shows the monthly hydrogen production variations of the PVT system during 2017. Similar to output electrical power, hydrogen production rises as the mean daily solar radiation increases. The maximum hydrogen production is calculated 2.99 kg in June for proposed PVT system utilizing Mono-Crystalline Semitransparent PV.

Total energy and exergy efficiencies besides H₂ production for different PV and PCM modules are tabulated in Table 6. The maximum total energy efficiency is obtained for the PVT unit with Mono-Crystalline Semitransparent PV module and RT35 PCM for Aug 16 (35.04%). While the maximum total exergy efficiency is calculated for the system with Mono-Crystalline Semitransparent PV module and 120 kg of RT28 PCM type for winter (15.17%). Referring to Table 6, the maximum hydrogen production is 88.71 gr for the system with Mono-Crystalline Semitransparent PV module and 120 kg of RT35 for Aug 16. Because the solar radiation intensity and consequently the generated electricity are higher and the PV temperature related to RT 35 is the lowest during the summer. It is worth mentioning that the PVT system with RT28 is not simulated for summer, because the ambient temperature for Aug 16 is higher than its melting point for the major part of the day. Moreover, both RT50 and RT44 have approximately the same efficiencies and almost similar hydrogen production amount for Mar 14. Because these PCMs do not melt during the day, since the ambient temperature and solar radiation intensity is low and consequently do not reserve energy in the latent form.

6. Conclusions

In the present study, an electrical and thermal model of a PVT unit integrated with PEM electrolyzer and PCM installed beneath the PVT is developed for the purpose of electricity and hot water generation. The electricity generated by the proposed unit is

![Fig. 12. Hourly variation of a. Electrical and b. Thermal exergy efficiencies during the day with and without PCM for 14 Mar. and 16 Aug.](image1)

![Fig. 13. Hourly hydrogen production for 14 Mar. and 16 Aug. with and without PCM.](image2)
utilized to electrolyze water so as to generate hydrogen as a clean fuel. System performance is investigated as well as the effects of various parameters on the system's operation. The main results and conclusions drawn from the results and findings follow:

- Since the PCM saves a major proportion of input energy, the PV temperature declines, and consequently its efficiency increases for the PVT system with PCM.
- During nighttime, the PCM responds as an energy source for the system and keeps the water warm inside the storage tank.
- The PVT unit with Mono-Crystalline Semitransparent PV module possesses higher efficiency in comparison with Poly-Si PV type due to higher \( h_0 \).
- Results show that the PCM type influences the temperatures of system components. Regarding the higher latent heat capacity of the PCM, it can reserve more energy leading to lower temperatures and higher efficiency.
- The PCM mass is one of the effective parameters of the system performance. Low PCM masses lead to small total heat capacity. Therefore, the efficiency of the combined unit falls by reducing the PCM mass.
- Produced electrical and thermal energies rise by applying PCM and increasing the solar radiation intensity. In addition, for summer, these parameters are higher than those calculated for the winter.
- Electrical energy efficiency for Mar 14 is higher than that for Aug 16, due to the lower ambient temperature. Moreover, electrical and thermal energy efficiencies for the system with the PCM is higher than those for the unit without PCM.
- Output electrical and thermal exergies behave like output ones. Therefore, the PVT unit without PCM has lower output exergies comparing with the system with PCM.
- The rate of hydrogen production has a direct relationship with solar radiation intensity. Hence, it is higher for summer. Furthermore, the system produces higher amounts of hydrogen when it is integrated with the PCM.
- The maximum daily hydrogen production by the proposed PVT system is calculated for Aug 16 using Mono-Crystalline Semitransparent PV and 120 kg of RT35 (88.71 gr/day) which is 5.32% higher than that for the system without PCM.
- Maximum generated electrical power and hydrogen during 2017 are obtained for June, when the mean daily solar radiation is maximum (26.8 MJ/m².day).

**Table 6**

Total energy and exergy efficiencies, and \( H_2 \) production for different PV and PCM modules.

<table>
<thead>
<tr>
<th>PV type</th>
<th>PCM type</th>
<th>( \eta_{total} (%) )</th>
<th>14 Mar</th>
<th>16 Aug</th>
<th>( \eta_{ex, total} (%) )</th>
<th>14 Mar</th>
<th>16 Aug</th>
<th>( m_{H_2} (gr) )</th>
<th>14 Mar</th>
<th>16 Aug</th>
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<tr>
<td>Mono-crystalline semitransparent PV</td>
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<tr>
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<td>Without PCM</td>
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**Fig. 14.** Monthly production of a. Electrical power and b. Hydrogen for 2017.

**Appendix A. Supplementary data**

Supplementary data to this article can be found online at [https://doi.org/10.1016/j.jclepro.2019.01.022](https://doi.org/10.1016/j.jclepro.2019.01.022).

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Fars Province Meteorological Administration. Shiraz, Iran.


