Corresponding Author: M.A.M. Rosli, Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia.

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Abstract: A photovoltaic/thermal (PV/T) device is a combined solar thermal device and photovoltaic device in a single unit. The capability of PV/T devices to produce thermal energy and electricity simultaneously bestows them promising market value in near future. The higher specific heat and lower fluctuation during variation irradiance of liquid compared to air make liquid-based devices more advantageous. This study reviews the available literature on flat plate, water-based PV/T collectors, conducts an economic analysis and discusses future development. Detailed analysis of the performance of the device is also included, in terms of thermal, electrical and overall efficiency. Previous experimental work and simulations are also reported, including several selected case studies. Some of the drawbacks need to be solved to make water-based PV/T systems cost effective and ready for the market.

Key words: Absorber • Collector • Photovoltaic thermal • Water based • Hybrid PV/T

INTRODUCTION

The oil crisis in the early 1970s and the environmental concerns in the 1990s have changed the global outlook on energy use. Increasing oil and gas prices, as well as carbon emissions from fossil fuel, is a global problem that needs to be overcome. Total global energy consumption was 495 quadrillion Btu in 2007 and is predicted to increase by 49% from 2007 to 2035. The energy demand for fossil fuels accounts for 86%, renewable energy for 8% and nuclear energy for 6% of the total global energy consumption [1]. Given the depletion of fossil fuel and the global issue of greenhouse gases, renewable energy applications have elicited intense research interest, particularly in the fields of engineering and science [2]. Renewable energy can be considered as clean energy [3] because it allows the production of greenhouse gas-free electrical energy and heat [4]. Such clean energy is important to a healthy future [5].

The hybrid photovoltaic thermal (PV/T) system is a type of renewable energy resource. PV/T technology combines a photovoltaic (PV) module and a traditional solar thermal device in a single unit [6]. The thermal system converts solar energy into thermal energy and the photovoltaic device simultaneously converts solar energy into electrical energy [3, 7]. PV/T technology is a promising renewable energy resource for the future. Improving overall performance and lowering costs will make PV/T technology more competitive in the market [6, 8].

Research on PV/T has been carried out over the last 25 years [7], with many researchers seeking to fully utilize collected solar energy [9]. PV/T is the most effective solar collector, using sunlight and thermal energy simultaneously [10]. Depending on the type of cell, PV devices convert 5 to 20% of incoming irradiance into electricity energy, with the residual percentage being transformed into heat [11, 12, 13]. A lower temperature is needed for higher electrical efficiency, owing to a negative temperature coefficient [13]. Therefore, using working fluid as heat removal can increase the efficiency of PV devices. Chow et al. [14] noted that crystalline silicon PV devices reduce operating temperature by approximately 0.0045%/°C. Meanwhile, the amorphous silicon PV is
lower compared with crystalline silicon cells [15]. Thus, amorphous silicon PV devices demonstrate stable long-term operation at high temperatures [16, 17].

Based on the energy, cost and exergy involved, PV/T systems are efficient solar energy conversion devices [18]. Some of the advantages of PV/T systems are stated as follows [8, 11, 19]:

- **Bifunctionality**: they produce electrical energy and heat simultaneously
- **Efficiency**: the combined efficiency is always higher than that of independent systems [7, 20].
- **Flexibility**: most suitable for areas with limited space; consistently higher efficiency per unit area [7, 20, 21].
- **Various applications**: can be used for heating or cooling depending on the season (desiccant)
- **Cost effectiveness and practicality**: can be easily mounted on existing roofs with minimal modifications, which can reduce the payback period [21, 22].
- **Better aesthetics**: more uniform than side-by-side systems [17, 23].
- **Longer equipment lifespan**: releases thermal stress by means of cooling process
- **Improved thermal comfort**: reduces air conditioning load [14]
- **Water works better as a working fluid than air, thereby increasing electrical energy yield** [22, 24].

Cristofari et al. [4] conducted an experiment for a photovoltaic/thermal (PV/T) system collector using copolymer material as absorber. They obtained average rates of 29, 14 and 43 to 65% for thermal, electrical and overall efficiencies, respectively. They also addressed several advantages of using copolymer material, which are as follows:

- **Inexpensive**
- **Easy to handle**
- **Weight is twice lighter than traditional collectors**
- **Satisfies chemical constraints**
- **Satisfies thermal mechanical constraints**
- **Performs similarly as metal absorber**
- **Reduces manufacturing cost because of its less expensive cost compared with copper**
- **Saves production time**

**Categories of PV/T**: The PV/T system can be categorized in several ways because of the vast development of research on PV/T. Classification of PV/T can be narrowed down by the type of working fluid, mode of fluid movement, installation and thermal collector arrangement which can either be conventional flat plate or embedded with concentrator [20]. Jin-Hee Kim and Jun-Tae Kim classified PV/T as either glazed or unglazed units [25]. PV/T can also be classified based on the type of demand that refers to high- or low-temperature application [11]. Figure 1 shows the typical classification of PV/T based on type of working fluids.

**PV/T Water Collector**: PV/T water collector is the most popular type compared to other types of working liquids, such as refrigerant and air, or combination of both. The main reasons behind this popularity are the cost, applications and properties of PV/T water collector [7, 8].

Tripanagnostopoulos et al. [26] conducted an experiment for a hybrid PV/T system using different types of PV modules, namely, polycrystalline and amorphous silicon. The variations of the experiment included the heat extractor fluids and the presence of glazing and reflector. They found that heat removal using water is more efficient compared to air in all cases. Furthermore, high electrical efficiency is obtained because of its high thermal efficiency.

Most PV/T water collectors produce water heating for domestic applications. The target water temperature is 60°C [27]. The effective range of collector area for hot domestic water PV/T system is between 3 to 6 m² with 139 l per day at 60°C [15].

**Main Components**: Flat plate PV/T collectors are similar to established flat collectors; the only obvious difference is that in the former, the PV module is attached on top of the absorbers. The main components of flat plate PV/T water collectors are the PV module, adhesive, absorber and insulator. The adhesive consists of ethylene-vinyl acetate and a layer of tedlar [22].

The purpose of the absorber, also called an “extracting heat device” is to reduce the temperature underneath the PV module. The water flowing inside the tubes transport the collected thermal energy in low-temperature applications, such as water heating [7]. The insulator prevents heat from escaping into the surrounding area. Glass covers are optional for PV/T systems and can either be single or double glass. PV/T devices with more than three glass covers are not recommended because their electrical efficiency is very low [15]. The absorber/water tube design for PV/T water collectors can be classified into two groups:
Fig. 1: Classification of PV/T collector

- Sheet and tube/serpentine [13, 21, 22, 28, 29, 30, 31].
- Parallel flow channel [8, 11, 28].

Zondag et al. [15] studied nine different designs of PV/T collectors that were categorized into four groups, namely, channel, sheet and tubes, free flow and two absorber PV/T collectors. The channel PV/T collector showed the best overall efficiency. However, the design of the sheet and tubes was more practical because of ease of manufacturing. Moreover, the deleterious effects of its energy expenditure only worsen by 2% annually.

Issues and Challenges: Maggio and Cacciola argued that the use of renewable energy has disadvantages and limitations [1]. The following are some challenges and issues for the PV/T hybrid system.

- The thermal efficiency of a PV/T collector is lower than that of a thermal collector because of the high emissivity and lower absorptivity of the PV laminate. Consequently, the absorption of the PV laminate is less than that of the thermal collector because the laminate does not behave as a black absorber and a portion of the absorbed energy is converted to electrical energy [13, 18].
- The PV/T–PV/T water collector is more efficient than the air PV/T collector because water has more thermophysical properties than air [24]. However, using the air-based collector is more practical because of its minimum operational cost [8]. Given that the PV/T–PV/T water collector requires piping for water circulation, it is therefore more costly than the PV/T air collector [12].
- The operation of the PV/T system is limited because this system is not suitable in places with hot climate over a long period. The cell efficiency of this system declines significantly after a certain duration of operation as well as when problems with water freezing occur [17]. Cooling the PV cell in hot and humid climates is not a simple task given the lack of an efficient cooling method for PV/T panels when the environmental temperature increases during the day [32].

Development of PV/T Water Collector Design for a Last Decade: The performances of the PV/T water depending on various aspects. The development design of the PV/T water collector has been study in term of design, operating conditions and material selection. Table 1 shows selected development of the PV/T water collector design for a last decade. The study includes the parameter of collector, layer of glass, type of PV and material chosen as absorber and shape of the design.

Performance on PV/T Collectors: The performance of a PV/T collector is basically derived from that of a hybrid flat plate solar thermal collector and PV module [11, 28]. Florschuetz [33] enhanced the original Hottel–Whillier model to analyze the flat plate PV/T collector. He stated that a well-established Hottel–Whillier model based on a solar energy research is advantageous for the direct use of existing relations and extensions.

Thermal Efficiency Collectors: The thermal efficiency, \( \eta_h \) is the ratio of the useful thermal energy, \( Q_u \) to irradiance, \( G \). It can be written as below:

\[
\eta_h = \frac{Q_u}{G}
\]
Table 1: Selected development of PV/T water collector design

<table>
<thead>
<tr>
<th>Year</th>
<th>Water collector design</th>
<th>Collector material</th>
<th>Type of PV Glazing</th>
<th>Electrical</th>
<th>Thermal</th>
<th>Overall</th>
<th>Remarks</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>ST + RT</td>
<td>CP</td>
<td>N.A</td>
<td>N.A</td>
<td>N.A</td>
<td>0.6-0.8</td>
<td>Parametric study</td>
<td>[34]</td>
</tr>
<tr>
<td>1997</td>
<td>ST + RT</td>
<td>AL</td>
<td>PC</td>
<td>UG, 1</td>
<td>N.A</td>
<td>N.A</td>
<td>Electrical performance for coverless 8% more than single cover</td>
<td>[10]</td>
</tr>
<tr>
<td>2001</td>
<td>ST + RT</td>
<td>AL</td>
<td>PC</td>
<td>UG, 1</td>
<td>0.389</td>
<td>0.09</td>
<td>Introduce primary energy saving which exceed 60% for cold starts.</td>
<td>[21]</td>
</tr>
<tr>
<td>2002</td>
<td>ST + SRT</td>
<td>PB</td>
<td>MC</td>
<td>I</td>
<td>N.A</td>
<td>N.A</td>
<td>Solar cell temperature strongly correlated to the water inlet system.</td>
<td>[26]</td>
</tr>
<tr>
<td>2002</td>
<td>ST + RT + REF</td>
<td>CP</td>
<td>PC</td>
<td>UG, 1</td>
<td>N.A</td>
<td>N.A</td>
<td>PV/T water glazing with booster diffuse reflector obtains highest thermal and electrical output.</td>
<td>[26]</td>
</tr>
<tr>
<td>2003</td>
<td>WC + A, ST + RT + FF</td>
<td>N.A</td>
<td>N.A</td>
<td>0, 1, 2</td>
<td>N.A</td>
<td>N.A</td>
<td>Conduct experiment for glazing cover, opaque and transparent PV, free flow and two absorbers.</td>
<td>[15]</td>
</tr>
<tr>
<td>2003</td>
<td>ST + RT</td>
<td>CP</td>
<td>N.A</td>
<td>I</td>
<td>N.A</td>
<td>N.A</td>
<td>Explicit dynamic model for PV/T water.</td>
<td>[22]</td>
</tr>
<tr>
<td>2005</td>
<td>ST + RT</td>
<td>AL</td>
<td>N.A</td>
<td>I</td>
<td>N.A</td>
<td>N.A</td>
<td>Adopted low solar concentrator.</td>
<td>[37]</td>
</tr>
<tr>
<td>2006</td>
<td>ST + SRT</td>
<td>AL</td>
<td>PC</td>
<td>1</td>
<td>0.123</td>
<td>0.574</td>
<td>0.697 100% covered by PV</td>
<td>[26]</td>
</tr>
<tr>
<td>2006</td>
<td>ST + RT</td>
<td>AL</td>
<td>PC</td>
<td>1</td>
<td>0.121</td>
<td>0.668</td>
<td>0.789 50% covered by PV</td>
<td>[26]</td>
</tr>
<tr>
<td>2006</td>
<td>WC + A, ST + RT</td>
<td>N.A</td>
<td>N.A</td>
<td>UG, 1</td>
<td>N.A</td>
<td>0.4</td>
<td>Not cover by PV</td>
<td>[17]</td>
</tr>
<tr>
<td>2006</td>
<td>WC + A, ST + RT</td>
<td>N.A</td>
<td>N.A</td>
<td>I</td>
<td>N.A</td>
<td>0.58</td>
<td>50% PV cover the absorber surface.</td>
<td>[38]</td>
</tr>
<tr>
<td>2007</td>
<td>ST + SRT</td>
<td>N.A</td>
<td>PC</td>
<td>1</td>
<td>0.0856</td>
<td>0.389</td>
<td>Parametric study on unglazed, glaze, with and without tedlar.</td>
<td>[39]</td>
</tr>
<tr>
<td>2007</td>
<td>ST + SRT</td>
<td>N.A</td>
<td>MC</td>
<td>1</td>
<td>0.101</td>
<td>0.45</td>
<td>Validate thermal model</td>
<td>[30]</td>
</tr>
<tr>
<td>2007</td>
<td>ST + SRT</td>
<td>N.A</td>
<td>MC</td>
<td>1</td>
<td>0.119</td>
<td>0.3489</td>
<td>Daily primary-energy saving up to 65%. The PV/T water was designed with natural circulation.</td>
<td>[40]</td>
</tr>
<tr>
<td>2009</td>
<td>ST + SRT</td>
<td>N.A</td>
<td>N.A</td>
<td>I</td>
<td>N.A</td>
<td>N.A</td>
<td>Analysis PV/T connected in series with 5 different weather conditions.</td>
<td>[41]</td>
</tr>
<tr>
<td>2009</td>
<td>ST + SRT</td>
<td>SL</td>
<td>PC</td>
<td>1</td>
<td>0.119</td>
<td>0.3489</td>
<td>Develop 7 design of absorber.</td>
<td>[42]</td>
</tr>
<tr>
<td>2009</td>
<td>ST + RT</td>
<td>SL</td>
<td>N.A</td>
<td>I</td>
<td>N.A</td>
<td>N.A</td>
<td>Spiral designs obtain highest efficiency.</td>
<td>[41]</td>
</tr>
<tr>
<td>2009</td>
<td>ST + RT</td>
<td>PC</td>
<td>N.A</td>
<td>I</td>
<td>0.12</td>
<td>0.55</td>
<td>Partially and fully covered connected in series on five different cities in India</td>
<td>[41]</td>
</tr>
<tr>
<td>2009</td>
<td>ST + RT</td>
<td>PC</td>
<td>N.A</td>
<td>I</td>
<td>0.12</td>
<td>0.55</td>
<td>Primary energy saving is 0.88</td>
<td>[4]</td>
</tr>
<tr>
<td>2010</td>
<td>ST</td>
<td>CP</td>
<td>MC AS</td>
<td>CIGS</td>
<td>I</td>
<td>N.A</td>
<td>Electrical and thermal efficiency decrease with the increase of Solar Fraction (SF).</td>
<td>[13]</td>
</tr>
<tr>
<td>2011</td>
<td>ST + RT</td>
<td>CP</td>
<td>PC</td>
<td>1</td>
<td>0.088</td>
<td>0.79</td>
<td>Adopted anti reflecting coating and low emissivity coating.</td>
<td>[27]</td>
</tr>
<tr>
<td>2011</td>
<td>ST, RT</td>
<td>CP</td>
<td>MC</td>
<td>1</td>
<td>0.098</td>
<td>0.40</td>
<td>Optimization of the single glazing PV/T.</td>
<td>[27]</td>
</tr>
<tr>
<td>2011</td>
<td>ST</td>
<td>CP</td>
<td>N.A</td>
<td>I</td>
<td>N.A</td>
<td>N.A</td>
<td>Comparative study on PV/T and conventional collector under natural circulation of fluid.</td>
<td>[38]</td>
</tr>
<tr>
<td>2012</td>
<td>ST + RT</td>
<td>N.A</td>
<td>PC</td>
<td>UG</td>
<td>0.12</td>
<td>0.35</td>
<td>Low flow concept to reduce pump power consumption.</td>
<td>[43]</td>
</tr>
<tr>
<td>2012</td>
<td>ST + RT</td>
<td>PL</td>
<td>PC</td>
<td>1</td>
<td>0.14</td>
<td>0.29</td>
<td>Water tank storage able to reach up to 40°C</td>
<td>[44]</td>
</tr>
<tr>
<td>2012</td>
<td>ST + RT</td>
<td>AL</td>
<td>PC</td>
<td>1</td>
<td>N.A</td>
<td>N.A</td>
<td>Primary-energy saving up to 65%.</td>
<td>[45]</td>
</tr>
<tr>
<td>2012</td>
<td>ST + RT</td>
<td>CP</td>
<td>N.A</td>
<td>I</td>
<td>N.A</td>
<td>N.A</td>
<td>Recommend manifold to riser ratio of 4:1 to improve uniformity.</td>
<td>[46]</td>
</tr>
<tr>
<td>2012</td>
<td>ST + RT</td>
<td>CP</td>
<td>N.A</td>
<td>I</td>
<td>N.A</td>
<td>N.A</td>
<td>Parametric study on heat pipe PV/T. Application for the cold regions without becoming frozen.</td>
<td>[47]</td>
</tr>
</tbody>
</table>
The useful thermal energy can be obtained by multiplying mass flow rate, \( \dot{m} \) heat capacitance \( (C_p) \) of flowing fluid and temperature difference between outlet \( (T_o) \) and inlet of fluid \( (T_i) \).

\[
Q_u = \dot{m}C_p(T_o - T_i)
\] (2)

The useful energy also can be expressed by net absorbed solar irradiance after removed the amount of heat losses and produced electrical energy by the PV module. The overall energy loss coefficient is determined by sum of the losses of the top, side and below of collector [53]. The major losses mainly caused by top loss which was the radiation heat transfer between glasses to ambient temperature by low wind velocity [54].

\[
Q_u = Ac[S - U_L(T_{p,m} - T_d)]
\] (3)

where, \( U_L \) is overall heat loss coefficient, \( A \) is a collector area, \( S \) is an irradiance and transmissance-absorptivity \( G(\tau) \) and \( T_{p,m} \) is the mean absorber plate temperature. The \( T_{p,m} \) parameter is complex to calculate and measure due to the function of absorber design. Li et al. [2] mentioned the characteristic of solar collector not only dependent on absorber material but also the geometry, type of thermal insulator, thickness of cover which significantly affect the optical and heat loss coefficient. To simplify the analysis due to the variation design of PV/T collector, the equation for a flat plate collector by Hottel-Whillier was modified by replacing the \( T_{p,m} \) to temperature inlet of fluid, \( T_i \).

\[
Q_u = AF_o[S - U_L(T_i - T_d)]
\] (4)

where, \( F_o \) is the heat removal factor which related with the efficiency factor, \( F' \) and fin efficiency, \( F \) using the following equation:

\[
F_o = \frac{GC_p}{U_LF'} \left[ 1 - \exp \left( -\frac{U_LF'}{GC_p} \right) \right]
\] (5)

Knowing water as a working fluid, the \( F' \) can be determined by using following equation:

\[
F' = \frac{1}{U_L} \left[ \frac{1}{W} \frac{1}{U_L[D_o + (W - D_o)F]} + \frac{1}{C_h} + \frac{1}{mD_hh_f} \right]
\] (6)

where, \( W \) is the gap between tubes, \( D_o \) and \( D_i \) are the outer and inner diameter of the tubes, \( C_h \) is the bonding conductivity between fin and tubes and \( h_f \) is heat transfer coefficient of working fluid in the tubes. \( F \) is the fin efficiency and can be described by:

\[
F = \frac{\tanh(x)}{x}
\] (7)

and \( x \) is given by:
where \( k \) and \( \delta \) is the thermal conductivity and thickness of the fin.

### Electrical Efficiency

The equation of the electrical efficiency \((\eta_{el})\) of a PV module can be expressed as:

\[
\eta_{el} = \frac{P_o}{G A_e} = \frac{I_m V_m}{G A_e}
\]  

(9)

The performance of a photovoltaic module decreases as temperature increases, as given by the equation below

\[
\eta_e = \eta_o (1 - \beta(T_p - T_{ref}))
\]  

(10)

where, \( \eta_e \) is the electrical efficiency at standard temperature conditions or at the reference temperature of 25°C on 1000 W/m², \( \beta \) is the cell efficiency temperature coefficient, \( T_p \) is the photovoltaic cell temperature that depends on environmental conditions and while \( T_{ref} \) is the reference temperature. Normally the value of \( \eta_o \), \( T_{ref} \) and \( \beta \) are generally given by the manufacturer. The value of \( \beta \) is also depends on the PV module materials. Most available PV modules are converted into electricity with a peak efficiency that ranges from 5 to 20% [7, 48].

From the equation (10), the performance of PV/T strongly depends on the operating temperature. Al Harbi et al. [35] conducted an experiment on PV/T water systems in Saudi Arabia. The results showed good thermal performance but 30% lower electrical efficiency. During the winter session, the thermal performance dropped as expected, whereas electrical yield was higher than that during summer. They concluded that the PV/T system was not suitable for Riyadh climate, owing to the high environmental temperature during summer (35°C). The thermal performance was high, but the decrease in electrical yield during the afternoon reduced the electrical efficiency of the PV module.

Shuang-Ying Wu et al. [20] examined the temperature variation underneath the PV module during the process flow of the working fluid and found that an adjustable heat pipe can be integrated into the PV/T collector to ensure a uniform operating temperature. Their theoretical and experimental results indicated that the overall thermal, electrical and exergy efficiency reached 63.65, 8.45 and 10.26%, respectively. The operating temperature varied by less than 2.5°C.

### Overall Efficiency of PV/T: Marc Baetschmann and Hansjürg Leibundgut [58] argued that the concepts of building heat and electricity supply cannot be evaluated independently and require analyses in the integrated system. According to Huang et al. [21], the overall efficiency of PV/T systems can be obtained by:

\[
\eta_o = \eta_{th} + \eta_{el}
\]  

(11)

Given that thermal efficiency and electrical efficiency are different forms of energy, modifying the equation above to evaluate the energy saving of PV/T systems is convenient. As defined by energy saving efficiency or primary energy saving, the modified equation can be written as:

\[
E_{fr} = \frac{\eta_o}{\eta_{power}} + \eta_{th}
\]  

(12)

where \( \eta_o \), electrical efficiency, \( \eta_{power} \) is the electrical power generation for conventional power plant (0.38) and \( \eta_{th} \) is the thermal energy [21]. Tiwari et al. [6] noted that the overall thermal efficiency of a PV/T system can be obtained using the following equation:

\[
\eta_{overall\ thermal} = \frac{\eta_{th} + \frac{\eta_{electrical}}{\eta_{cp}}}{\eta_{ocp}}
\]  

(13)

where, the value of \( \eta_{oc} \) refers to the quality of coal in term of ash content. The ranges of \( \eta_{oc} \) between 0.2-0.4.

### Economic Analysis Review for PV/T System

The energy payback period is significantly reduced when PV efficiency is increased [30]. According to Chow et al. [17], the payback period for plain PV devices can be reduced by implementing a PV/T collector system. To prove this claim, they conducted an economic analysis of four solar collector systems, namely, solar water heating system, PV system, side-by-side system and PV/T system. They found that payback for the PV/T system is only 12 years, whereas that of the plain PV system is 52 years. They also found that the payback period for the PV/T collector system is about the same as that of the conventional side-by-side system. They also pointed out that a payback period higher than 15 years is not practical for commercialization.

Based on the Italian climate, Ghani et al. [59] noted that PV/T collectors improve the energy payback to 2 years whereas that of a separate solar thermal system is about 4.3 years.
Basant Agrawal and Tiwari, conducted a life cycle cost assessment using Matlab 7 software, taking into account the initial cost, maintenance cost, replacement cost and salvage values. They found that the cost of unit power generation of amorphous silicon (a-Si) building integrated photovoltaic thermal (BIPVT) system is almost the same as that of the conventional grid in New Delhi [60].

Tiwari et al. [6] concluded that CIGS solar cell technology is most suitable for BIPVT systems in terms of energy payback period and energy production factor. However, in terms of lifecycle conversion efficiency, monocrystalline cells are most suitable for BIPVT systems. Anderson et al. [61] stated that the rear insulation for BIPVT systems can be embedded inside attics for lower natural convection heat transfer rather than in conventional insulation layers for PV/T systems, thereby reducing material costs. They also stressed that the material used for absorbers do not undergo significant changes in terms of thermal and electrical performance. Therefore, using less expensive materials, such as steel, is an option despite their low thermal conductivity. Kalogirou [31] conducted a transient analysis using TRNSYS and concluded that by reducing the initial cost, the low value of the optimum mass flow rate (25 l/h) makes it possible for the system to run in thermosyphon mode.

Tripanagnostopoulos et al. estimated that using hybrid PV/T system using water and air is more expensive that using plain polycrystalline PV modules by 8 and 5%, respectively. Including the piping and circulation pump, the total cost is increased by 10 and 8%, respectively. Despite producing the same thermal output, the cost of amorphous silicon (a-Si) modules is about double that of pc-Si hybrid PV/T systems [26].

Coventry and Lovegrove proposed a method that can be used to determine an optimal PV/T system for domestic use. They considered the methods of exergy, open market and a renewable energy market. Based on levelized energy cost and comparison of the ratios of electrical and thermal energy output, they found that the most suitable approach is the renewable energy market because of its practicality. However, a-Si is preferable to c-Si when the energy value ratio is lower than 4.5 [16].

Wei He et al. [38] compared the natural circulation mode of water in a PV/T device, a conventional solar thermal device and a PV module and found that the daily efficiency of the PV/T device was 40%, which is 75% of the efficiency of the traditional solar thermal collector. The average daily electrical efficiency was found to be approximately 10% and only slightly lower than that of a monocrystalline silicon photovoltaic plate under the same conditions. The primary energy saving was about 60 to 75% greater than that of the conventional solar thermal system. The researchers also stated that natural circulation offers a space requirement advantage because no pump is used, thereby providing extra energy. This system has excellent potential for use in the domestic market.

**Technique to Enhance Performance of PV/T Water:** A few techniques are used to enhance the performance of PV/T water system. These techniques can be classified in terms of design, such as the physical parameter of the PV/T and the operating condition of the system and environment. In this paper, several parameters that affect the performance of PV/T water system are identified. 

**Glass cover**

In general, the high numbers of glass cover increase thermal efficiency but decrease electrical efficiency. Zondag et al. reported that PV/T single-cover sheet and tube is suitable for domestic hot water because of its efficiency and ease of manufacturing [15]. Meanwhile, Dupeyrat et al. [27] proposed the use of anti-reflection coat for glass cover, with a transmission coefficient of 0.94.

Chow et al. [62] studied the energy and exergy efficiencies of glazed and unglazed PV/T collectors. The experimental and numerical models are developed for glazed and unglazed covers. Based on six operating factors, specifically ambient temperature, irradiance, cell efficiency, wind speed, PV cell covering factor and ratio of mass water to collector area, they found that the glazed PV/T collector always performs is desired in terms of thermal efficiency. However, in terms of exergy efficiency, the unglazed PV/T collector is better than the glazed PV/T collector. In general, the significant factors for the glazed collector are side solar irradiance and ambient temperature, whereas the remaining factor significantly affects the unglazed PV/T collector system.

Instead of the layer of glazing, Dubey and Tiwari [63] studied the percentage covered PV/T by PV. They carried out an analytical analysis for the PV/T system (glass to glass) and then validated the experiment for three design configurations, which are 100% covered by PV glass-to-glass module, 50% covered at the bottom and 30.56% partially covered and connected in series. The three design configurations strongly agree with each other and the best instantaneous efficiency of 30.56% is obtained from the partially covered design configuration because of its high glazing area exposure.
In terms of exergy, Fujisawa and Tani [10] conducted an annual experiment to evaluate the exergy for water-based PV/T collector system. This approach was used because electrical and thermal efficiencies are different in nature. They developed four design configurations: PV, flat plate collector (FPC), PV/T collector with single glaze and coverless. They found that the best to least performance in terms of producing energy gain was in the following order: single-cover PV/T > FPC > coverless PV/T > and PV, with gains of 614, 575, 480 and 72.6 kWh/yr, respectively. On the contrary, in exergy (available energy) evaluation, the order is as follows: coverless PV/T collector > PV module > single-cover PV/T > FPC, with gains of 80.9, 72.6, 71.5 and 6 kWh/year, respectively.

**Effective Area of PV to Collector:**

The effective area of PV to Collector affects the electric yield of PV/T. Mishra and Tiwari [49] conducted an experiment for the two groups of PVT collectors under constant temperatures. The configurations were case A (collector partially covered by PV) and case B (collector fully covered by PV). The temperature was maintained by changing the mass flow rate using the temperature sensor. Both cases were compared to the FPC in terms of thermal energy, electrical energy and exergy gain.

According to the investigators, case A was more satisfactory for the thermal energy, whereas case B was favorable for electricity generation. Based on the numerical calculations, the annual thermal energy gains of 4167.3 and 1023.7 and annual net electrical energy gains of 320.65 and 1377.63 were obtained for cases A and B, respectively. Moreover, the annual overall exergy gain of case A increased to 39.16% compared to case B.

**Mass Flow Rate:**

The mass flow rate is one of the important operating parameters in running the PV/T system. The mass flow rate should be sufficient enough to absorb the heat on the collector. Cristofari et al. [4] studied the thermal behavior of PV/T in low flow rates (0.007 kg/s). They used copolymer material as absorber exchanger. They claimed that the thermal performance for copolymer PV/T design was 55.5% and the electrical efficiency was 12.7%. The total efficiency was 68.2% and the primary energy saving was 88.8%.

In addition, the uniformity of the mass flow affects the PV efficiency of the PV/T collector system. Ghani et al. [59] conducted about 100 simulations with various designs, geometry shapes (aspect ratio) and operational parameters (mass flow rate and flow directions). They found that the performance for the most uniform flow increased by 9% efficiency, whereas improper mass flow rate only improved by 2%. To obtain optimum flow distribution, they suggested that the manifold-to-riser ratio should be in the range of 4:1 to 6:1 and the aspect ratio of array must be greater than 0.44 to obtain good electric yield.
Future Development: The availability of PV/T systems is dependent on cost, design, material, fabrication, technology, technical issues and efficiency. Most researchers have struggled to determine the optimum PV/T configuration that offers the best quality in terms of performance and cost effectiveness.

According to Pathak et al. [18], hydrogenated amorphous silicon (a-Si:H) is a promising material because of its temperature coefficient of about $-0.01\%/{ }^\circ C$, which is one fourth that of typical C-Si [18]. Adnan Ibrahim et al. argued that the PV/T system can be improved in terms of absorber collector design, payback period and system manufacturability [66]. The researchers designed PV/T collectors of various shapes and found that the highest performance (without considering manufacturing cost) was exhibited by the spiral-shaped collector constructed from stainless steel [67].

Using compound parabolic concentrator PV collectors is more advantageous than using common FPCs because of the higher efficiency and fewer photovoltaic cells of the former [68]. Li et al. [2] conducted an experiment using a through concentrating photovoltaic thermal (TCPV/T) system involving three types of crystal silicon and a GaAs cell array. The researchers found that the electrical efficiency of the GaAs cell array was better than that of the crystal silicon cell, but the thermal performance of the silicon base was better because the width of the cell crystal silicon was close to the focal line. Li et al. also mentioned that the TCPV/T systems have good economic prospects because their electricity generation cost is close to that of conventional flat plate PV systems [2].

Xingxing Zhang et al. observed that refrigeration-based PV/T and heat pipe-based PV/T are two promising devices. A maximum electrical efficiency of around 10% and thermal efficiency of about 58 to 65% make both devices very competitive [28]. Tripanagnostopoulos [12] suggested dual PV/T type collectors with both water and air systems that can alternate as a working fluid to extract heat depending on the season or thermal need of the system. Tripanagnostopoulos integrated the diffuse reflector and low-cost concentrator to enhance the electrical and thermal output, claiming that this combination is cost effective and suitable for buildings with horizontal rooftops [12].

Majed Ben Ammar et al. [69] proposed a novel PV/T control algorithm based on artificial neural network (ANN). This system works by detecting an optimum power operation point (OPOP) based on multivariable PVT characteristics and a nonlinear model. The system computes the mass flow rate, irradiance and ambient temperature. Simulation results show good agreement between the OPOP model based on calculation and the ANN output.

Ghani et al. [59] proposed an ANN that can be used to estimate the electrical PV yield of an array, including the specific shape and direction of flow. Using an unglazed BIPV system, the results of the numerical analysis is varied by changes in the manifolds, riser ratio, mass flow rate, direction of flow, flow distribution and the limitations of the roof area. However, varying customer requirements make the PV yield difficult to predict and time consuming to resolve. Therefore, ANNs offer a fast alternative to the conventional numerical approach, making it a very convenient approach for computing size-specific electrical energy requirements based on various configurations for each building installation [59].

Cristifori et al. [45] proposed a PV/T collector without air layers. The product is made of copolymer material, which is less expensive, easier to handle and lighter than traditional collectors by more than half. The absorber copolymer material satisfied the chemical, thermal and mechanical constraints and performed in the same manner as the metal absorber. This product obtained an average thermal, electrical and overall efficiency of 29, 14 and 43 to 65%, respectively.

CONCLUSION

This study summarizes the vast research conducted by a number of researchers for the last 35 years in the fields of design, system development, experiments and simulations concerning water-based PVT collectors. Water-based PV/T systems consist of PV modules and an absorber to extract the heat underneath the PV module, thereby enhancing electrical efficiency and providing thermal energy simultaneously. Using water as a working fluid is very practical because of its availability, cost effectiveness and properties. Solar energy conversion provided by a single unit has good prospects in the face of upcoming energy demands.

Water-based PV/T devices fulfill the electrical and heat needs of various applications and fields, such as residential units, schools, prisons, hospitals, food services, laundry, water desalination, solar green houses and agriculture. Classified as low-thermal applications,
these devices can be used to meet the growing energy demand of the coming years. The research done across various fields indicate the massive prospects of PV/T hybrids in multi-purpose applications.

As a general conclusion, the available literature shows that the flat plate water-based PV/T collector is a very promising device. The advantages of the system and its wide application offer smarter choices for consumers and industries. Increased efficiency and lower costs will make the PV/T collector more competitive as a solar conversion device.

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REFERENCES

Persian Abstract

PV/T تلفیقی از حرارت خورشیدی و دستگاه فتوولتایک در یک واحد می‌باشد. ظرفیت دستگاه PV/T برای تولید حرارت و جریان برق پیوند تیتانیم بارز آینده را تسخیر خواهد کرد. گرمای ویژگی بالا و تغییرات اندازه ناشی موجب می‌شود که در نظر گرفته شود. این دستگاه‌ها در صحنه سالر و نیز در سیستم‌های انتخاب شده است. تحلیل شده با برطوره نمودن معایب سیستم‌باید قابل بازاریابی باشد.

BIPV/T یک نمونه از نمادها در زمینه انتخاب مناسب است. این نمونه با تناسب کلاک‌های آبی و زهی به‌طور کامل و با نگرانی در نظر گرفته شد.


