Iranica Journal of Energy & Environment 5 (4): 407-418, 2014
ISSN 2079-2115
IJEE an Official Peer Reviewed Journal of Babol Noshirvani University of Technology
DOI: 10.5829/idosi.ijee.2014.05.04.09

BUT

Progress on Flat-Plate Water Based of Photovoltaic Thermal (PV/T) System: A Review

[1,2]M.A.M. Rosli, [1]S. Mat, [1]M.K. Anuar, [1]Kamaruzzaman Sopian, [1]M.Y. Sulaiman and [1]S. Ellias

[1]Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[2]Faculty of Mechanical Engineering Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya, 76100 Duran Tunggal, Melaka, Malaysia

Received: July 21, 2014; Accepted in Revised form: October 5, 2014

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

Corresponding Author: M.A.M. Rosli, Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia. E-mail: afzanizam@utem.edu.my.

Please cite this article as: M.A.M. Rosli, S. Mat, M.K. Anuar, Kamaruzzaman Sopian, M.Y. Sulaiman and S. Ellias, 2014. Progress on Flat-Plate Water Based of Photovoltaic Thermal (PV/T) System: A Review. Iranica Journal of Energy and Environment, 5 (4): 407-418.

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 m^2 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 to 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:

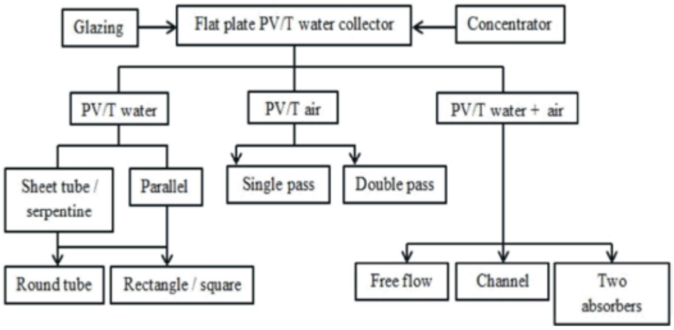

Fig. 1: Classification of PV/T collector

- 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 cost of producing electricity via a photovoltaic device is several times higher than that using a conventional fossil fuel [14] and requires higher investment cost per kilowatt of installed capacity [1].
- 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, (η_{th}) is the ratio of the useful thermal energy, (Q_u) to irradiance, (G). It can be written as below:

$$\eta_{th} = \frac{Q_u}{G} \tag{1}$$

Table 1: Selected development of PV/T water collector design

					Efficiency				
Year	Water collector design	Collector material	Type of PV	Glazing	Electrical	Thermal	Overall	Remarks	Ref
1979	ST + RT	N.A	N.A	1	N.A	N.A	N.A	Hottel - Whillier model extend	[33]
1995	ST + RT	CP	N.A	1	N.A	N.A	0.6-0.8	Parametric study	[34]
1997	ST + RT	AL	PC	UG, 1	N.A	N.A	N.A	Electrical performance for coverless 8% more than single cover	[10]
1998	ST + RT	CP	N.A	UG	N.A	N.A	N.A	Climate of Saudi Arabia	[35]
2001	ST + RT	AL	PC	UG	0.389	0.09	0.475	Introduce primary energy saving which exceed 60% for cold starts.	[21]
2002	ST + SRT	PB	MC	1	N.A	N.A	N.A	Solar cell temperature strongly correlated to the water inlet system.	[36]
2002	ST + RT + REF	CP	PC	UG, 1	N.A	N.A	N.A	PV/T water glazing with booster diffuse reflector obtains highest thermal and electrical output.	[26]
2003	WC+A, ST + RT + FF	N.A	N.A	0, 1, 2	N.A	N.A	N.A	Conduct experiment for glazing cover, opaque and transparent PV, free flow and two absorbers.	[15]
2003	ST + RT	CP	N.A	1	N.A	N.A	N.A	Explicit dynamic model for PV/T water.	[22]
2005	ST + RT	AL	N.A	1	N.A	N.A	> 0.6	Adopted low solar concentrator.	[37]
2006	ST + SRT	AL	PC	1	0.123	0.574	0.697	100% covered by PV	
					0.121	0.668	0.789	50% covered by PV	
					-	0.763	0.763	Not cover by PV	[17]
2006	ST + RT	AL	PC	1	N.A	0.4	N.A	50% PV cover the absorber surface.	[38]
2006	WC + A, ST + RT	N.A	N.A	UG,1	N.A	N.A	N.A	Parametric study on unglazed, glaze, with and without tedlar.	[39]
2006	WC + A, ST + RT	N.A	N.A	1	N.A	0.58	N.A	Validate thermal model	[30]
2007	ST + SRT	N.A	PC	1	0.0856	0.389	N.A	Collector mounted vertical façade Hong Kong climate. Natural circulation of working fluid preferable.	[14]
2007	ST + SRT	AL	MC	1	0.101	0.45	0.52	Daily primary-energy saving up to 65%. The PV/T water was design with natural circulation.	[40]
2009	ST + SRT	N.A	N.A	1	N.A	N.A	N.A	Analysis PV/T connected in series with 5 different weather conditions.	[41]
2009	ST + SRT	SL	PC	1	0.119	0.3489	N.A	Develop 7 design of absorber. Spiral designs obtain highest efficiency.	[42]
2009	ST + RT	SL	N.A	1	N.A	N.A	N.A	Partially and fully covered connected in series on five different cities in India	[41]
2009	ST + RT	PC	N.A	1	0.12	0.55	0.68	Primary energy saving is 0.88	[4]
2010	ST	CP	MC AS CIGS	1	N.A	N.A	N.A	Electrical and thermal efficiency decrease with the increase of Solar Fraction (SF). Adopted anti reflecting coating and low emissivity coating.	[13]
2011	ST + RT	CP	PC	1	0.088	0.79	0.88	Optimization of the single glazing PV/T.	[27]
2011	ST, RT	CP	MC	1	0.098	0.40	0.51	Comparative study on PV/T and conventional collector under natural circulation of fluid.	[38]
2011	ST	CP	N.A	1	N.A	N.A	N.A	Low flow concept to reduce pump power consumption.	[43]
2012	ST + RT	N.A	PC	UG	0.12	0.35	0.47	Water tank storage able to reach up to 40°C	[44]
2012	ST + RT	PL	PC	1	0.14	0.29	0.43	Primary-energy saving up to 65%.	[45]
2012	ST + RT	AL	PC	1	N.A	N.A	N.A	Recommend manifold to riser ratio of 4:1 to improve uniformity.	[46]
2012	ST + RT	CP	N.A	1	N.A	N.A	N.A	Parametric study on heat pipe PV/T. Application for the cold regions without becoming frozen.	[47]

Table 1: Continued

2013	ST + RT	CP	MC	1	0.118	0.407	N.A	Tropical climate.	[48]
	SRT	CP	PC	1	0.114	0.394	N.A	PV/T electrical efficiency is higher 0.4% compared normal PV modules.	
2013	ST + RT	N.A	N.A	1	0.104 0.100	0.459 0.282	N.A N.A	Two cases: Collector partially and fully covered by semitransparent PV. Recommendation to regulate mass flow rate to achieve constant temperature.	[49]
2013	ST + RT	N.A	MC	1	N.A	N.A	N.A	Evaluation of PV/T performance under hot climate conditions - Saudi Arabia.	[50]
2013	ST + SRT	N.A	N.A	1	N.A	N.A	N.A	Conclude less series connected PV module, the lower inlet temperature and high flow rate resulted in the high photovoltaic efficiency.	[51]
2014	ST + SRT	N.A	MC	UG, 1	N.A	N.A	N.A	Comparative study on standard PV, solar collector and PVT suing TRSYS and experiment.	[52]

Legend:

AL	Aluminum	MC	Mono crystalline	PL	Polymer	SRT	Single / rectangle tube
AP	Amorphous silicon	PB	Polycarbonate	RT	Round tube	ST	Sheet and tube
CP	Copper	SL	Steel	UG	Unglazed	WC	Water collector
FF	Free flow	PC	Poly crystalline	SP	Spiral	N.A	Not available

WC+A Combination water and air collector

The useful thermal energy can be obtains by multiplying mass flow rate, () heat capacitance (C_p) of flowing fluid and temperature different between outlet (T_o) and inlet of fluid (T_i).

$$Q_u = \dot{m}C_p(T_o - T_i) \tag{2}$$

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].

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

where, U_L is overall heat loss coefficient, A_c is a collector area, S is an irradiance and transmittance-absorptivity $G(\tau\alpha)$ 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.

$$Q_u = A_cF_R[S - U_L(T_i - T_a)] \tag{4}$$

where, F_R is the heat removal factor which related with the efficiency factor, F' and fin efficiency, F using the following equation:

$$\frac{F_R}{F'} = \frac{GC_P}{U_LF'}\left[1 - \exp\left(-\frac{U_LF'}{GC_p}\right)\right] \tag{5}$$

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

$$F' = \frac{\dfrac{1}{U_L}}{w\left[\dfrac{1}{U_L[D_o + (W - D_o)F]} + \dfrac{1}{C_b} + \dfrac{1}{mD_ih_{fi}}\right]} \tag{6}$$

where, W is the gap between tubes, D_o and D_i are the outer and inner diameter of the tubes, C_b is the bonding conductivity between fin and tubes and h_{fi} is heat transfer coefficient of working fluid in the tubes. F is the fin efficiency and can be described by:

$$F = \frac{tanh(x)}{x} \tag{7}$$

and x is given by:

$$x = \sqrt{\frac{U_L}{k\delta}}\left(\frac{W - D_o}{2}\right) \quad (8)$$

where k and δ is the thermal conductivity and thickness of the fin.

Electrical Efficiency: The equation of the electrical efficiency (η_{el}) of a PV module can be expressed as:

$$\eta_{el} = \frac{I_m V_m}{GA_c} = \frac{P_o}{GA_c} \quad (9)$$

The performance of a photovoltaic module decreases as temperature increases, as given by the equation below [4, 55, 56, 57].

$$\eta_{el} = \eta_o\,(1 - \beta[T_{pv} - T_{ref}]) \quad (10)$$

where, η_o is the electrical efficiency at standard temperature conditions or at the reference temperature of 25°C on 1000 W/m^2, β is the cell efficiency temperature coefficient, T_{pv} is the photovoltaic cell temperature that depends on environmental conditions and while T_{ref} is the reference temperature. Normally the value of η_o, T_{ref} and β are generally given by the manufacturer. The value of β 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:

$$\eta_o = \eta_{th} + \eta_e \quad (11)$$

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:

$$E_f = \eta_o/\eta_{power} + \eta_{th} \quad (12)$$

where η_e electrical efficiency, n_{power} is the electrical power generation for conventional power plant (0.38) and η_{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:

$$\eta_{overall\ thermal} = \eta_{th} + \frac{\eta electrical}{\eta_{cp}} \quad (13)$$

where, the value of η_{cp} refers to the quality of coal in term of ash content. The ranges of η_{cp} 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 glaze 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.

Fin Performance: The fin performance is a crucial factor in achieving high efficiency of PV/T water system [22], [26], [61]. The fin is also known as the gap of tubes arranged equally through the panel width and bond on the absorber plate [62]. The bond conduction (C_b) is very important for metal-to-metal contacts in obtaining low resistance values [64].

Bergene and Lovvik proposed fin configurations on the PV/T collector system. Based on their algorithm predictions, thermal efficiency is about halved when the ratio of fin width-to-diameter is (WD^{-1}) increased in the range of 1 to 10 with constant width [65]. Reducing the space of tube improved the PV/T water efficiency but resulted in cost increase [47]. This drawback needs to be addressed in designing the PV/T collector.

Absorber: The absorber is the most crucial part in determining the performance of PV/T water system. Aste et al. [56] conducted a simulation of a PVT absorber using FLUENT 13.0 software. They developed three-dimensional models to investigate the temperature distribution on serpentine and harp (parallel) absorbers. When comparing each collector, the total length and the ratio between tube spaces for each collector were set to be similar. They concluded that the parallel absorber was better than the serpentine in all electrical configurations. The simulations were conducted in steady state.

Apart from the typical PV/T water collector design, Adnan *et al.* [66] also evaluated seven other design configurations of absorber collectors, namely, direct flow, serpentine flow, parallel–serpentine flow, modified serpentine flow, oscillatory flow, spiral flow and web flow designs. They found that the best absorber collector design was the spiral, with overall efficiency of 64%. The electrical efficiency was 11% at 55°C (on module) and mass flow rate of 0.011 kg/s. This result is ascribed to the high contact area of the absorber that enhances the heat transfer mechanism to the working fluid.

Effective Area of PV to Collector: The area of PV 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%/°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 PVT 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 AAN 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 BIPVT collector, 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 roofing 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.

ACKNOWLEDGEMENT

The author highly acknowledges the Solar Energy Research Institute, Universiti Kebangsaan Malaysia and Universiti Teknikal Malaysia Melaka for sponsoring this work.

REFERENCES

1. Maggio, G. and G. Cacciola, 2012. When will oil, natural gas and coal peak?. Fuel, 98: 111-23.
2. Li, M., G.L. Li, X. Ji, F. Yin and L. Xu, 2011. The performance analysis of the Trough Concentrating Solar Photovoltaic/Thermal system. Energy Conversion Management, 52: 2378-83.
3. Solanki, S.C., S. Dubey and A. Tiwari, 2009. Indoor simulation and testing of photovoltaic thermal (PV/T) air collectors. Applied. Energy, 86: 2421-28.
4. Cristofari, C., G. Notton and J.L. Canaletti, 2009. Thermal behavior of a copolymer PV/Th solar system in low flow rate conditions. Solar Energy, 83: 1123-38.
5. Hein, K.R.G., 2005. Future energy supply in Europe-challenge and chances. Fuel, 84: 1189-94.
6. Tiwari, G.N., R.K. Mishra and S.C. Solanki, 2011. Photovoltaic modules and their applications: A review on thermal modelling. Applied Energy, 88: 2287-304.
7. Charalambous, P.G., G.G. Maidment, S.A. Kalogirou and K. Yiakoumetti, 2007. Photovoltaic thermal (PV/T) collectors: A review. Applied Thermal Engineering, 27: 275-86.
8. Tyagi, V.V., S.C. Kaushik and S.K. Tyagi, 2012. Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology. Renewable Sustainable Energy Review, 16: 1383-98.
9. Naewngerndee, R., E. Hattha, K. Chumpolrat, T. Sangkapes, J. Phongsitong and S. Jaikla, 2011. Finite element method for computational fluid dynamics to design photovoltaic thermal (PV/T) system configuration. Solar Energy Material Solar Cells, 95: 390-3.
10. Fujisawa, T. and T. Tani, 1997. Annual exergy evaluation on photovoltaic-thermal hybrid collector. Solar Energy Material Solar Cells, 47: 135-48.
11. Hasan, M.A. and K. Sumathy, 2010. Photovoltaic thermal module concepts and their performance analysis: A review. Renewable Sustainable Energy Review, 14: 1845-59.
12. Tripanagnostopoulos, Y., 2007. Aspects and improvements of hybrid photovoltaic/thermal solar energy systems. Solar Energy, 81: 1117-31.
13. Santbergen, R., C.C.M. Rindt, H.A. Zondag and R.J.C. Van Zolingen, 2010. Detailed analysis of the energy yield of systems with covered sheet-and-tube PVT collectors. Solar Energy, 84: 867-78.
14. Chow, T.T., W. He and J. Ji, 2007. An experimental study of façade-integrated photovoltaic/water-heating system. Applied Thermal Engineering, 27: 37-45.
15. Zondag, H.A., D.W. De Vries, W.G.J. Van Helden, R.J.C. Van Zolingen and A.A. Van Steenhoven, 2003. The yield of different combined PV-thermal collector designs. Solar Energy, 74: 253-69.
16. Coventry, J.S. and K. Lovegrove, 2003. Development of an approach to compare the "value’ of electrical and thermal output from a domestic PV / thermal system. Solar Energy, 75: 63-72.
17. Chow, T.T., W. He and J. Ji, 2006. Hybrid photovoltaic-thermosyphon water heating system for residential application. Solar Energy, 80(3): 298-306.
18. Pathak, M.J.M., J.M. Pearce and S.J. Harrison, 2012. Effects on amorphous silicon photovoltaic performance from high-temperature annealing pulses in photovoltaic thermal hybrid devices. Solar Energy Material Solar Cells, 100: 199-203.
19. Garg, H.P. and R.K. Agarwal, 1995. Some aspects of a PV/T collector/forced circulation flat plate solar water heater with solar cells. Energy Conversion Management, 36: 87-99.
20. Wu, S.Y., Q.L. Zhang, L. Xiao and F.H. Guo, 2011. A heat pipe photovoltaic/thermal (PV/T) hybrid system and its performance evaluation. Energy Building, 43: 3558-67.

21. Huang, B., T. Lin, W. Hung and F. Sun, 2001. Performance evaluation of solar photovoltaic/thermal systems. Solar Energy, 70: 443-8.
22. Chow, T.T., 2003. Performance analysis of photovoltaic-thermal collector by explicit dynamic model. Solar Energy, 75: 143-52.
23. Dupeyrat, P., C. Ménézo, H. Wirth and M. Rommel, 2011. Improvement of PV module optical properties for PV-thermal hybrid collector application. Solar Energy Material Solar Cells, 95: 2028-36.
24. Chen, H. and P. Wei, 2011. Energy Procedia Numerical Study on a Novel Photovoltaic / Thermal Heat Pump System. Energy Procedia, 12: 547-53.
25. Kim, J. and J. Kim, 2012. "The experimental performance of an unglazed PV-thermal collector with a fully wetted absorber. Energy Procedia, 30: 144-51.
26. Tripanagnostopoulos, Y., T.H. Nousia, M. Souliotis and P. Yianoulis, 2002. Hybrid photovoltaic / thermal solar systems. Solar Energy, 72: 217-34.
27. Dupeyrat, P., C. Ménézo, M. Rommel and H.M. Henning, 201. Efficient single glazed flat plate photovoltaic-thermal hybrid collector for domestic hot water system. Solar Energy, 85: 1457-68.
28. Zhang, X., X. Zhao, S. Smith, J. Xu and X. Yu, 2012. Review of R&D progress and practical application of the solar photovoltaic/thermal (PV/T) technologies. Renewable Sustainable Energy Review, 16: 599-617.
29. Zondag, H.A., D.W. De Vries, W.G.J. Van Helden, R.J.C. Van Zolingen and A.A. Van Steenhoven, 2002. The thermal and electrical yield of a PV-thermal collector. Solar Energy, 72: 113-28.
30. Tiwari, A. and M.S. Sodha, 2006. Performance evaluation of solar PV/T system: An experimental validation. Solar Energy, 80: 751-9.
31. Kalogirou, S.A., 2001. Use of TRNSYS for modelling and simulation of a hybrid pv-thermal solar system for Cyprus. Renewable Energy, 23: 247-60.
32. Daghigh, R., M.H. Ruslan and K. Sopian, 2011. Advances in liquid based photovoltaic/thermal (PV/T) collectors. Renewable Sustainable Energy Review, 15: 4156-70.
33. Florschuetz, L.W., 1979. Extension of the hottel-whillier model to the analysis of combined photovoltaic / thermal flat plate collectors. Solar Energy, 22: 361-6.
34. Tronde Bergene, O.M.L., 1995. Model calculations on a flat-plate solar heat collector with integrated solar cells. Solar Energy, 55(6): 453-462.
35. Harbi, Y.A.L., N.N. Eugenio and S.A.L. Zahrani, 1998. Photovoltaic-Thermal Solar Energy Experiment in Saudi Arabia. Renewable Energy, 5: 5-8.
36. Sandnes, B. and J. Rekstad, 2002. A photovoltaic/thermal (PV/T) collector with a polymer absorber plate. Experimental study and analytical model. Solar Energy, 72(1): 63-73.
37. Rosell, J.I., X. Vallverdú, M.A. Lechón and M. Ibáñez, 2005. Design and simulation of a low concentrating photovoltaic/thermal system. Energy Conversion Management, 46(18-19): 3034-3046.
38. He, W., Y. Zhang and J. Ji, 2011. Comparative experiment study on photovoltaic and thermal solar system under natural circulation of water. Applied Thermal Engineering, 313369-76.
39. Tiwari, A. and M.S. Sodha, 2006. Performance evaluation of solar PV/T system: An experimental validation. Solar Energy, 80: 751-9.
40. Ji, J., J.P. Lu, T.T. Chow, W. He and G. Pei, 2007. A sensitivity study of a hybrid photovoltaic/thermal water-heating system with natural circulation. Appl. Energy, 84(2): 222-237.
41. Dubey, S. and G.N. Tiwari, 2009. Analysis of PV/T flat plate water collectors connected in series. Solar Energy, 83(9): 1485-1498.
42. Ibrahim, A., M.Y. Othman, M.H. Ruslan, M.A. Alghoul, M. Yahya, A. Zaharim and K. Sopian, 2009. Performance of Photovoltaic Thermal Collector (PVT) With Different Absorbers Design. WSEAS Trans. Environ. Development, 5(3): 321-330.
43. Charalambous, P.G., S.A. Kalogirou, G.G. Maidment and K. Yiakoumetti, 2011. Optimization of the photovoltaic thermal (PV/T) collector absorber. Solar Energy, 85(5): 871-880.
44. Huang, C., H. Sung and K. Yen, 2012. Experimental Study of Photovoltaic / Thermal (PV / T) Hybrid System. Int. J. Smart Clean Energy, pp: 148-151.
45. Cristofari, C., J.L. Canaletti, G. Notton and C. Darras, 2012. Energy Procedia Innovative patented PV / TH Solar Collector?: optimization and performance evaluation. Energy Procedia, 14: 235-240.
46. Ghani, F., M. Duke and J. K. Carson, 2012. Effect of flow distribution on the photovoltaic performance of a building integrated photovoltaic/thermal (BIPV/T) collector. Solar Energy, 86: 1518-30.
47. Gang, P., F. Huide, Z. Huijuan and J. Jie, 2012. Performance study and parametric analysis of a novel heat pipe PV/T system. Energy, 37: 384-95.

48. Dubey, S. and A.A.O. Tay, 2013. Energy for Sustainable Development Testing of two different types of photovoltaic - thermal (PVT) modules with heat flow pattern under tropical climatic conditions. Energy Sustainable Development, 17: 1-12.
49. Mishra, R.K. and G.N. Tiwari, 2013. Energy and exergy analysis of hybrid photovoltaic thermal water collector for constant collection temperature mode. Solar Energy, 90: 58-67.
50. Bahaidarah, H., A. Subhan, P. Gandhidasan and S. Rehman, 2013. Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions. Energy, 59: 445-453.
51. Shan, F., L. Cao and G. Fang, 2013. Dynamic performances modeling of a photovoltaic-thermal collector with water heating in buildings. Energy Building, 66: 485-494.
52. Dupeyrat, P., C. Ménézo and S. Fortuin, 2014. Study of the thermal and electrical performances of PVT solar hot water system. Energy Building, 68: 751-755.
53. Amori, K.E. and H.M. Taqi Al-Najjar, 2012. Analysis of thermal and electrical performance of a hybrid (PV/T) air based solar collector for Iraq. Applied Energy, 98: 384-95.
54. Klein, S.A., 1975. Calculation of flat-plate collector loss coefficients. Solar Energy, 17: 79-80.
55. Vats, K. and G.N. Tiwari, 2012. "Energy and exergy analysis of a building integrated semitransparent photovoltaic thermal (BISPVT) system. Applied Energy, 96: 409-16.
56. Aste, N., C. Del Pero and F. Leonforte, 2012. Thermal-electrical optimization of the configuration a liquid PVT collector. Renewable Energy, 30: 1-7.
57. Lee, Y. and A.A.O. Tay, 2012. Energy Procedia Finite Element Thermal Analysis of a Solar Photovoltaic Module. Energy Procedia, 15: 413-20.
58. Baetschmann, M. and H. Leibundgut, 2012. LowEx solar building system?: Integration of PV / T collectors into low exergy building systems. Energy Procedia, 30: 1052-9.
59. Ghani, F., M. Duke and J.K. Carson, 2012. Estimation of photovoltaic conversion efficiency of a building integrated photovoltaic / thermal (BIPV / T) collector array using an artificial neural network. Solar Energy, 86: 3378-87.
60. Agrawal, B. and G.N. Tiwari, 2010. Life cycle cost assessment of building integrated photovoltaic thermal (BIPVT) systems. Energy Building, 42: 1472-81.
61. Anderson, T.N., M. Duke, G.L. Morrison and J.K. Carson, 2009. Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector. Solar Energy, 83: 445-55.
62. Chow, T.T., G. Pei, K.F. Fong, Z. Lin, A.L.S. Chan and J. Ji, 2009. Energy and exergy analysis of photovoltaic-thermal collector with and without glass cover. Applied Energy, 86: 310-6.
63. Dubey, S. and G.N. Tiwari, 2008. Thermal modeling of a combined system of photovoltaic thermal (PV/T) solar water heater. Solar Energy, 82: 602-12.
64. William, J.A.D. and A. Beckman, 1980. Solar Engineering of Thermal Processes. New York: John Wiley & Sons, Inc.
65. Martin, O.L.E., 1955. Model Calculations on a Flat Plate Solar Heat Collecotor with Integrated Solar Cells. Solar Energy, 55: 453-462.
66. Ibrahim, A., M.Y. Othman, M.H. Ruslan, S. Mat and K. Sopian, 2011. Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors. Renewable Energy Sustainable Energy Review, 15: 352-65.
67. Othman, M.Y., A. Ibrahim, G.L. Jin, M.H. Ruslan and K. Sopian, 2013. Photovoltaic-thermal (PV/T) technology - The future energy technology. Renewable Energy, 49: 171-4.
68. Guiqiang, L., P. Gang, Y. Su, Z. Xi and J. Jie, 2012. Energy Procedia Preliminary study based on building-integrated compound parabolic concentrators (CPC) PV / thermal technology. Energy Procedia, 15: 343-50.
69. Ben Ammar, M., M. Chaabene and Z. Chtourou, 2013/ Artificial Neural Network based control for PV / T panel to track optimum thermal and electrical power. Energy Conversion Management, 65: 372-380.

Persian Abstract

چکیده

دستگاه فتو ولتائیک حرارتی(PV/T) تلفیقی از حرارت خورشیدی و دستگاه فتوولتائیک در یک واحد می باشد. ظرفیت دستگاه PV/T برای تولید حرارت و جریان برق بطور همزمان بازار آینده را تسخیر خواهد کرد. گرمای ویژه بالا و تغییرات اندک تابش موجب مزیت چنین دستکاهها می شود. این مقاله مطالعات مربوط به واحدهایی با صفحه مسطح و واحد کلکتور آبی PV/T را از نظر اقتصادی تحلیل نموده و چگونگی تکامل آن در آینده را بحث می نماید. جزئیات کارایی واحد PV/T از نظر راندمان حرارتی و جریان برق بررسی می نماید. شرح تجارب دیگران و چند مورد خاص انتخاب شده است. نقاط ضعف کلکتور آبی و هزینه سیستم از نظر اقتصادی تجزیه و تحلیل شده و با برطرف نمودن معایب سیستم باید قابل بازاریابی باشد.