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Review on Energy and Exergy Analysis of Air and Water Based Photovoltaic Thermal (PVT) Collector

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Article Info	ABSTRACT
	Hybrid photovoltaic-thermal (PVT) collector has been developed by combining photovoltaic (PV) technology and solar thermal collector in one module. The combination of two technologies in the same module has the potential to reduce cost of materials and the required space also improves performance of collectors. The hybrid PVT collectors were designed to generate electrical and thermal energy simultaneously. PV technology converts solar radiation into electrical energy while solar thermal collector will be converting solar energy to thermal energy. The main components of PVT collectors are PV panel, absorber plate, working fluid and insulator. According to the previous research, PVT collectors were developed by using air and water as a heat transfer medium. The benefits of heat removal are increasing PV panel efficiency by removing excessive heat from module. Parameters affecting the overall performances of PVT collectors included mass flow rate, area of collector, irradiance and PV cell materials. This paper presents a review of energy and exergy analysis of air-based and water-based PVT collector with different designs. The performances of PVT collectors were studied using First Law and Second Law of Thermodynamics. This study has found that generally the energy and exergy efficiency are range from 40%-70% and 5%-25%, respectively.

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1. INTRODUCTION

The growth of population and economic development in most of the countries in this world has increased the global energy needs. The International Energy Agencies (IEA) pointed out that increasing energy consumption for developing countries is faster than developed countries, and they required almost double of their current capacity to fulfill the energy demand by the year 2020. It is also estimated that the total world energy consumption will be increasing by 44 % from 2006 to 2030 [1]–[3]. Therefore, an alternative energy source must determine to meet our energy requirements and for the preservation of conventional fossil fuels. Solar energy is one of the renewable energy sources and this clean energy has potential to meet a significant amount of the world's energy demand [4]–[7] . Basically, solar systems can be categorised into two types which are thermal systems and photovoltaic technology [8]–[10]. Thermal collector will convert solar energy to thermal energy whereas photovoltaic technology converts solar radiation into electricity. Generally, thermal collector and photovoltaic collector are used separately. However, according to the previous research, the combination of both technologies in one system has the potential to reduce the required space, the use of materials and the cost of installation.

This system has known as hybrid photovoltaic thermal (PV/T) technology [11-13]. Photovoltaic thermal (PVT) collector is a combination of photovoltaic (PV) module and thermal collector in a single unit

to generate electricity and thermal energy simultaneously. The main components of PVT collector are PV panel, absorber, working fluid and insulator. Research on PVT collector has been conducted over the last 25 years with the main objective of the research is to determine the most effective system of PVT to generate higher energy efficiency [14]. The hybrid PVT collector generated more energy per unit surface area than PV panel and thermal collector are used separately [15]. The energy conversion efficiency of solar radiation into electricity by PV panel ranges between 12% to 18%, and up to 80% of irradiance either reflected or turn into heat as stated by Agrawal in 2010 [16]. In the paper by Chow [17], he indicated that increasing the temperature of the PV panel reduces the efficiency which is every increase of 10°C caused a decrease in panel efficiency of 5%. However, few researchers [18]–[20] have suggested that the efficiency of the PV panel can be increase by removing excessive heat from PV panel using cooling fluids such as air and water.

The objective of this paper is to review the performances of PVT collectors with different types of working fluids such as air and water. In addition, the overall performances of the PVT collector can be evaluated both experimentally and numerically based on energy and exergy analysis of the systems. The reported data and results are tabulated to show an overall efficiency of the systems regarding to the thermal energy and electricity production, and also energy and exergy efficiency.

2. TYPES OF PVT COLLECTORS

As shown in Figure 1, PV/T collector can be categorized into air-based PV/T collector, water-based PVT collector, and combination of air and water as heat transfer fluids. PVT water collectors are more efficient than PVT air collectors due to high heat conductivity of water as compared to air. However, air-based PVT are cheaper and most popular because of the flexibility of PV collector that can be simply changed to a PVT collector with a few adjustments [21]. The main components of PVT collectors consist of a PV panel on the top which converts solar radiation into electrical energy [22], absorber plate, and insulator materials at the bottom of the collector as shown in Figure 2. The purpose of thermal absorber underneath the module is to capture the remaining energy and removes excessive heat from the module. While this process occurs, the temperature of PV panel decreases and thus improving its electrical efficiency. Therefore, the generation of both electricity and thermal energy allows these hybrid systems to have higher exergy [23] and produce greater energy efficiency compared to solar thermal and solar PV alone [24]. As reported by Adnan et al. [14], the best absorber collector design was the spiral, with energy efficiency of 64% compared to other design of absorber collectors such as direct flow, serpentine flow and oscillatory flow.
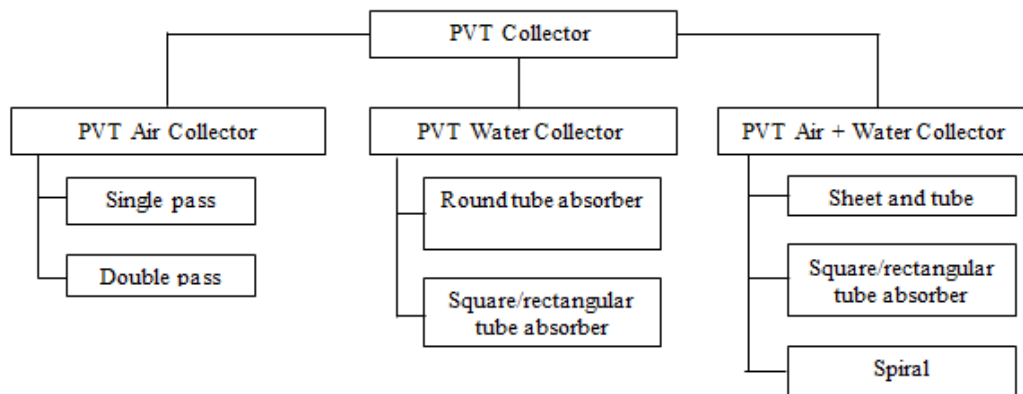

Figure 1. Classifications of PVT collectors [14]

Besides that, one of the important operating parameter in running the PVT collector is mass flow rate. The mass flow rate should be sufficient enough to absorb the heat in order to increase PV efficiency and thermal energy production. Fudholi et al. [25] did research on energy and exergy analysis of water based PVT collector with spiral flow absorber. The study showed that the energy efficiency varied from 58% to 68% and the PVT exergy efficiency ranged from 40% to 50% at the mass flow rate 0.011kg/s to 0.041kg/s and solar radiation of 800 W/m^2. In another research, Chandra et al. [26] developed an air type single-pass PVT collector with rectangular fins. They found that the maximum PV efficiency and thermal efficiency were obtained about 13.75% and 56.19% respectively for four fins at 0.14kg/s of mass flow rate. Apart from

typical PVT collector design, Othman et al. [27] conducted the performances analysis of PVT combi with water and air heating. The major components fabricated in the system are double-pass flat plat air collector and copper water tube. While the air flow rate and water flow rate was 0.05kg/s and 0.02kg/s, respectively, they determined the average electrical power generation achieved was 145W with electrical efficiency of 17% and thermal efficiency accomplished was 76%. Yet another research of PVT collector was presented by Tripathi et al. [28]. The study has highlighted the energy-exergy for partialaly covered concentrated PVT collector with water and dimethyl-diphenyl silicone fluid (DMDP) as a working fluid. The annual net gain for electrical, overall energy and exergy has been found as 12.35 kWh, 304.46 kWh and 50.58 kWh respectively.
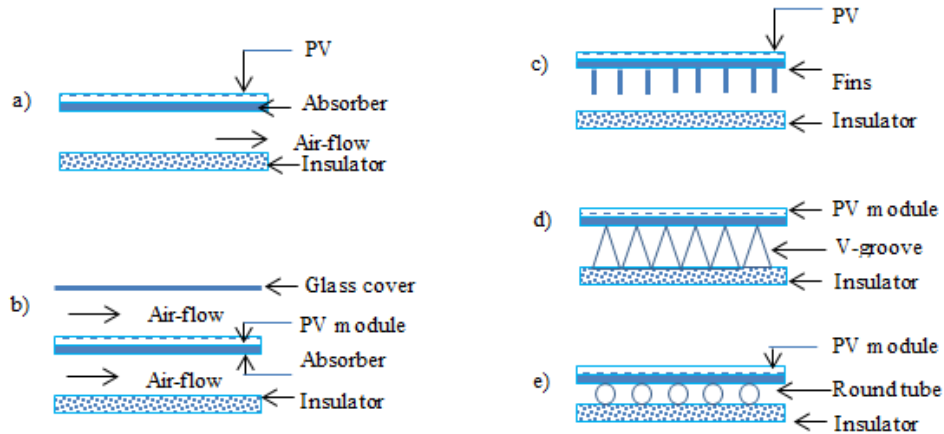

Figure 2. Cross-section of different types of PVT collectors. (a) Single pass air-based PVT collector, (b) Double pass air-based PVT collector, (c) PVT collector with fins, (d) PVT collector with v-groove absorber, (e) PVT collector with round tube absorber

In addition, the material of the PV solar cell affects the electric yield of PVT collector. PV solar cell materials can be catogarized into silicon solar cells, thin film solar cells and dye sensitized solar cells. According to Saini et al. [29], they discussed the electrical and thermal performance of N PVT-CPC collector with different types of solar cells. It was seen that the maximum net annual electrical anergy obtained for N PVT-CPC collector with monocrystalline solar cells is around 2 times higher than N PVT-CPC collector with amorphous thin film solar cells.

3. PERFORMANCE OF PVT COLLECTOR
3.1. Energy Analysis
The performance of PVT collectors can be represented by the sum of efficiency expression [30]. It is included of electrical efficiency (η_{PV}) and thermal efficiency (η_{th}), which are defined as the ratios of useful electrical gain and heat gain to incident solar radiation striking on the panel's collecting surface[25], [31], [32]. According to Huang et al. [33], the total energy efficiency of PVT (η_{PVT}) systems can be determined by:

$$\eta_{PVT} = \eta_{PV} + \eta_{th} \tag{1}$$

The electrical efficiency and thermal efficiency of a PVT collectors are, respectively given by [34]:

$$\eta_{PV} = \frac{I_m V_m}{S A_c} \tag{2}$$

$$\eta_{th} = \frac{mC(T_{out} - T_{in})}{S A_c} \tag{3}$$

where I_m and V_m are the electric current and voltage at maximum power point operation, S the incident solar

irradiation, A_c the area of the collector, m the mass flow rate of working fluid, C the specific heat capacity of the coolant, T_{in} and T_{out} the coolant (air or water) temperatures at the inlet and outlet. Basically, electrical efficiency also can be calculated in terms of module temperature is given as follows:
.

$$\eta_{PV} = \eta_{ref}[1 - \beta_{ref}(T_{pv} - T_{ref})] \tag{4}$$

where η_{ref} is reference efficiency of PV module, β_{ref} is temperature coefficient, T_{pv} is module temperature and T_{ref} is reference temperature.

3.2. Exergy Analysis

According to the previous research, PVT collector will produced the amount of energy in form of electrical and thermal energy. The maximum quantity of work that can be produced in some given environment named exergy. In addition, the work will has produced by thermal energy until a temperature difference exists between heat source and heat sink [35]. However, electrical energy can completely convert into work irrespective of the environment. Therefore, the exergy analysis can be created based on the second law of thermodynamics in terms of total exergy inflow (Ex_{in}), exergy outflow (Ex_{out}) and exergy destructed (Ex_{dest}) from the system. In PVT system, exergy balance can be expressed as:

$$Ex_{in} - Ex_{out} = Ex_{dest} \tag{5}$$

Where

$$Ex_{in} = ANS\left[1 - \left(\frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right)\right] \tag{6}$$

$$Ex_{out} = Ex_{PV} + Ex_{th} \tag{7}$$

where A is the area of the collector, N is collectors number, S is the incident solar radiation, T_a is the ambient temperature and T_s is the sun temperature in Kelvin. The electrical exergy (Ex_{PV}) and thermal exergy (Ex_{th}) can be written as follows:

$$Ex_{PV} = \eta_{PV}AS \tag{8}$$

$$Ex_{th} = mC(T_{out} - T_{in})\left[1 - \frac{T_a + 273}{T_{out} + 273}\right] \tag{9}$$

Therefore,

$$Ex_{PVT} = Ex_{PV} + Ex_{th} \tag{10}$$

where, Ex_{PVT} is photovoltaic thermal exergy, A is the PV area, and S is the incident solar radiation. So as a result of exergy analysis, the exergy efficiency ($\eta_{Ex_{PVT}}$) is the ratio of total exergy output to the total exergy input, then

$$\eta_{Ex_{PVT}} = \frac{Ex_{out}}{Ex_{in}} \tag{11}$$

Table 1 provides the result of energy and exergy analysis of PVT collectors as reported from different previous studies. It is found that most of the collectors could achieve a maximum energy efficiency and exergy efficiency of about 40%-75% and 5%-25%, respectively, for air and water cooled PVT collector. The overall performances of PVT collector efficiency depend on some parameters such as the type of working fluid, mass flow rate, PV cell materials, types of the absorber plate and area of the collector.

Table 1. Summary of Different PVT Collectors

Authors Ref.	Type of PVT Collectors	Energy Efficiency (%)			Exergy Efficiency (%)
		PV	Thermal	Overall	

Bosanac et al. [36]	Water-heating PVT and PVT air collector (PVT-Wall)	-	-	60	12
Joshi et al. [37]	PVT plate parallel air collector	-	-	55 – 65	12 – 15
Shahsavar et al. [38]	PVT collector with natural air flow	8 – 10	20 – 40	28 – 40	6 – 9
Fiorentini et al. [39]	PVT collector cooled by air with the addition of PCM	9	45	54	-
Hou et al. [40]	PVT systems combines with a micro heat pipe array	13	40	53	-
Wang et al. [41]	Heat pipe integrated with PVT (HP-PVT)	7.8	61.1	68.9	-
Tiwari et al. [42]	PVT flat plate collector (PVT-FPC)	-	25 – 53	-	5 – 18
Rounis et al. [43]	BIPVT systems with single and multiple-inlet for buildings	16.5	48	64.5	-
Fudholi et al. [25]	Water-based PVT collector with spiral flow absorber	13 –13.8	45 – 55	58 – 68	25
Agwaral et al. [44]	BIPVT system fixed on the rooftop of a building	7.13	33.54	40.67	-
Tiwari et al. [45]	PVT mixed mood greenhouse solar dryer	-	68.5	-	13.85

4. CONCLUSIONS

This paper reviewed the development in various design of PVT collectors that focused on the analysis of energy and exergy efficiencies. The electrical and thermal efficiency are also one of the most important parameter to be considered in PVT system. The review shows that, electrical efficiency is range from 10% to 25% and thermal efficiency are from 40% to 75%. The significant findings from this review are the energy and exergy efficiency of the PVT collectors are between 40%-70% and 5%-20%, respectively. According to the previous researches, the performances of the PVT collectors can be improved by modifiying the collector design. For the case of air-based PVT collectors, fins were attached at the flat-plat absorber in order to get larger heat transfer area. Therefore, higher the temperature drop experienced at the PV panel surface and thus panel efficiency will increase. In addition to the above modifications, water-based PVT collecter can be integrated with sheet-and-tube channel to increase heat transport.

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