Analysis of Hybrid System in the Photovoltaic and Photothermal Technology

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***Abstract*— The utilisation and optimisation of solar energy have a vital role in reducing the global need for conventional fossil energy. Moreover, it is also clean and eco-environmentally energy resources. The photovoltaic-thermal (PV-T) hybrid system that combines photovoltaic and photothermal technology is an ideal solution for creating high-efficiency energy conversion devices. In addition, this system can be constructed to be small and compact with a higher economic value than the conventional technology from the previous solar energy harvesters. This paper will review the PV-T hybrid system and provide the thermodynamic analysis and the feasibility study.**

***Keywords*— hybrid systems, photothermal, photovoltaic, solar energy**

I. Introduction

The global issue of the depletion of the ozone layer in recent decades has attracted the awareness of governments and researchers about the urgency to optimise renewable energy. Solar energy is the most promising resource among the available renewable energy resources because of its abundance and environmental friendliness in direct and indirect applications [1].

Solar energy harvesting methods can be divided into two types: photothermal (utilising heat energy) and photovoltaic (producing electrical energy). Photothermal system is widely used for post-processing in agricultural products (crop drying process to evaporate the water content), solar stoves, solar chimney, and hot water production for domestic household. On the other hand, photovoltaic technology can directly generate direct current (DC) electrical energy by exciting electrons in the semiconductor materials (such as silicon, germanium, tellurium, titanium dioxide, etc.) [2].

Solar photovoltaic panels have been recorded to produce electrical efficiency of 10-25% in the global market [2]. The price of solar panels is still relatively high, making applying this technology only possible for some purposes. Meanwhile, the photothermal system is recorded to have more than 50% thermal efficiency in producing hot water. The high thermal efficiency in a photothermal system is dominated by its ability to absorb the broader wavelength in solar irradiation [3].

Hybrid system that combines solar photovoltaic panel and solar photothermal collector, or PV-T systems, can produce the overall energy efficiency up to 70% [2]. Hybrid technology is an excellent system to be developed to improve its efficiency. This article will review the PV-T hybrid system that has been developed by researchers. It will provide the feasibility study of PV-T hybrid system for domestic and industrial applications.

II. Methods

A. *Hybrid system of photovoltaic-thermal (PV-T)*

A hybrid photovoltaic-thermal (PV-T) system is solar energy harvesting equipment that can produce both electricity and heat energy at the same time. Figure 1 shows the schematic and comparison of the PV-T system with the standalone PV panels and conventional solar collectors.

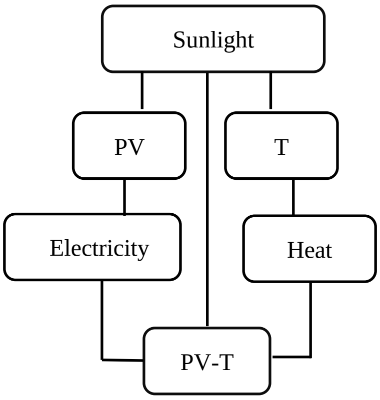

Fig. 1. Comparison of PV, thermal and hybrid PV-T systems [4]

Based on the working fluid in the PV-T hybrid system, it can be classified into three types: liquid, gas, or a combination of both fluids [5]. The air working fluid is usually used for space heating purposes, which are common in areas with four seasons, especially in the northern hemisphere. While the liquid working fluids generally utilise water, nanofluids, and anti-freeze fluids, which are needed for water heating purposes. In addition, the liquid can also be used as a working fluid in the heat pump system.

The application of the PV-T hybrid system is suitable in the limited land areas because it will minimise the space requirements. This system can also be integrated with the roof construction on the building. In France, installing a PV-T system has been tried in 30 locations with a range of 6 to 12 solar panels (1.5–2 kWp). Using a storage tank capacity of 300 liters, the results show that it can meet 65% of the hot water consumption for one family [6]. In addition, the PV-T system can decrease the PV panel's operating temperature. The low temperature in PV cell will increase its electrical efficiency and life durability. However, it has another effect to decrease the thermal performance of solar photothermal collectors.

Generally, the PV-T system uses pumps to operate its working fluid. However, it requires additional electrical energy. It will increase the operational cost of the PV-T system. Ref. [4] investigated the PV-T system using the

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thermosiphon concept. The thermosiphon principle uses buoyant force to drive the working fluid, thus, it doesn't require electrical energy to operate the pump [7]. The studied system in Ref [4] used a glazed flat-plate collector combined with two types of solar cells, polycrystalline and amorphous silicon, with an area of 4 m^2 and a storage tank of 160 litres of water. The results showed a decrease in heat energy production compared to conventional solar collector systems. However, it improved the electrical energy production of solar PV panels.

B. *Flat-Plate Thermal Collector*

Figure 2 shows the schematic of the hot collector configuration for the flat-plate type. In this study, an analysis from Ref [4] will be used to identify the performance of solar thermal collector. The energy generated from a heat collector ($\dot{Q}_u$) can be calculated based on the energy carried by the fluid using Equation 1.

$$\dot{Q}_u = \dot{m}c_p(T_{fo} - T_{fi}) \quad (1)$$

Where $\dot{m}$,c_p,T_{fo}, and T_{fi} are the mass flow rate, constant specific heat, inlet and outlet temperatures of the working fluid. $\dot{Q}_u$ can also be formulated based on the temperature of the absorber plate (T_{ap}) by using Equation 2.

$$\dot{Q}_u = A_c\left[S - U_L\left(T_{ap} - T_{amb}\right)\right] \quad (2)$$

Where A_c, S, U_L, T_{ap}, and T_{amb} are the collector areas, the absorbed solar irradiation, the coefficient of heat transfer losses, the absorber temperature, and the ambient temperature. This equation can also be simplified based on the fluid inlet temperature (T_{fi}) by using Equation 3.

$$\dot{Q}_u = A_cF_R\left[S - U_L\left(T_{fi} - T_{amb}\right)\right] \quad (3)$$

Where F_R is the heat loss factor, which can be calculated using Equation 4.

$$F_R = \frac{\dot{m}c_p}{A_cU_L}\left\{1 - exp\left(\frac{A_cU_LF_e}{\dot{m}c_p}\right)\right\} \quad (4)$$

With F_e is the collector efficiency factor, as shown in Equation 5.

$$F_e = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L}(D_o+(W-D_o)F_{fe})+\frac{1}{C_b}+\frac{1}{\pi D_i h_{fi}}\right]} \quad (5)$$

Where W, D_o, D_i, C_b, h_{fi}, and F_{fe} are the distances between the fluid pipes, the outer diameter, the inner diameter, the thermal conductivity of the fin and pipe joints, the fluid heat transfer coefficient, and the fin efficiency factor. Equation 6 can be used to calculate the fin efficiency factor (F_{fe}).

$$F_{fe} = \frac{tanh(x)}{x} \quad (6)$$

Where x is defined by equation (7)

$$x = \sqrt{\frac{U_L}{k\delta}}\left(\frac{W-D_o}{2}\right) \quad (7)$$

Where δ is the thickness of the fin. The thermal efficiency (η_{th}) of the flat-plate thermal collector under steady-state conditions can be formulated using Equation 8. Where G is the solar radiation intensity received by the collector.

$$\eta_{th} = \frac{Q_u}{G.A_c} \quad (8)$$

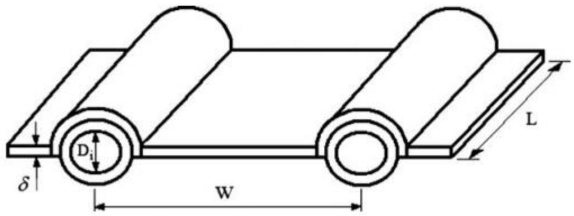

Fig. 2. Schematic of the absorber flat-plate thermal collector [4]

C. *Solar Photovoltaic Cell*

The efficiency of a solar cell shows its ability to convert radiated energy into electrical energy. There are three types of efficiency to characterize a solar cell's performance: energy, exergy, and power conversion efficiency [4]. Energy efficiency (η_e) is determined based on the ratio of a solar cell's theoretical output electric power divided by the received radiation value, as in Equation 9.

$$\eta_e = \frac{I_{sc}V_{oc}}{G.A_c} \quad (9)$$

Where I_{sc} and V_{oc} are the short circuit current and the open circuit voltage. The power conversion efficiency (η_{pce}) is determined based on the ratio of the area of the I-V solar cell's characteristic curve divided by the input irradiation, as shown in Equation 10.

$$\eta_{pce} = \frac{\int_0^{V_{oc}} I(V).dV}{G.A_c} \quad (10)$$

Meanwhile, the exergy efficiency (η_{ex}) is calculated based on the maximum usable energy of the solar cell divided by the input irradiation, as shown in Equation 11 [8].

$$\eta_{ex} = \frac{I_mV_m}{G.A_c} \quad (11)$$

The exergy efficiency can also be written by introducing the fill factor (FF) term, as shown in Equation 12.

$$\eta_{ex} = \frac{I_{sc}V_{oc}}{G.A_c}FF \quad (12)$$

In the converting of solar irradiation energy into electrical energy, solar cell only absorbs the small portion of the total

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available wavelength according to its semiconductor properties. Most of the solar irradiation energy that is not absorbed by the solar cell will be converted into heat energy, thereby it will increase the operational temperature [4]. The increasing temperature will also reduce the electrical efficiency of solar cells, which can be formulated by Equation 13.

$$\eta_e = \eta_{ref}\big(1 - \zeta(T - 25)\big) \tag{13}$$

Where η_{ref} is the reference efficiency of the solar cell when it is measured under the standard testing condition, G = 1000 W/m^2 and T = 25 °C. The ζ is the temperature coefficient of the solar cell's efficiency, which can be shown in Table 1.

TABLE 1. TEMPERATURE COEFFICIENT (ζ) FOR THE SOLAR CELLS' EFFICIENCY [9]

Type	ζ
Mono-Si	0.003-0.0041
Poly-Si	0.004
Amorphous-Si	0.0011-0.0026
PV-T system	0.004-0.0063

D. Efficiency of PV-T System

Based on the two fundamental devices about solar photovoltaic and solar photothermal system, the energy output of PV-T system is the sum of the two output energies (heat and electrical energies). Thus, the energy efficiency of the PV-T system (η_{ex-t}) is calculated in Equation 14.

$$\eta_{ex-t} = \frac{A_c F_R[S - U_L(T_{fi} - T_{amb})] + I_m V_m}{G.A_c} \tag{14}$$

III. RESULTS AND DISCUSSION

Based on the application of PV-T system, there are several important indicators that can be used to assess its suitability and feasibility levels. Ref. [6] shows at least four important indicators of the PV-T application process: electrical energy output, heat energy output, product availability, and the potential for building integration. Table 2 shows the comparative results of the study using three different models of PV-T systems.

TABLE 2. THE SUITABILITY LEVEL OF PV-T SYSTEMS [6]

Indicator	*Air-based PV-T*	*PV-T liquid (covered)*	*PV-T liquid (un-covered)*
Electrical energy	Increase	Decrease	Increase
Heat energy	Direct/ indirect	Direct/ indirect	Indirect
Availability	Low	Low	Medium
Integrity	High	Medium	Medium

The results indicate that PV-T systems that use air as its working fluid (air-based PV-T) is simple to integrate with buildings but it has limitation for space heating requirement. The liquid PV-T system with a collector cover is very suitable for direct application to supply hot water in the domestic house. Meanwhile, a liquid PV-T system without a collector cover is a suitable type of PV-T system when it is combined with a heat pump in the indirect application.

Using a solar collector's cover also dramatically affects the quantity of the energy output from the PV-T system. The cover can reduce the heat losses in the system so it can improve the heat energy production. However, it will negatively impact the solar PV panel's electrical efficiency. Because the efficiency of photovoltaic solar cells will be inversely proportional to the increasing of operating temperature [10-13]

Equation 15 shows the simple payback period (CPP) calculation to perform an economic study. where C_{CF} is the net annual cash flow, C_{FC} is the fixed capital cost, and C_S is the salvage value.

$$\sum_{t=0}^{t=SPP} C_{CF} = C_{FC} - C_S \tag{15}$$

An economic study conducted by Ref. [14] concluded that the PV-T system would have great economic value if applied to areas with high heat energy requirements and expensive land prices, such as the European region [15]. Calculating the value of the simple payback period (SPP) indicates that the PV-T system has a faster SPP value than the standalone solar PV panel system application, as shown in Table 3. These results show that the PV-T system will produce less heat energy when compared to conventional solar water heaters.

TABLE 3. CALCULATION OF THE SIMPLE PAYBACK PERIOD (SPP) [13]

Type	SPP (in years)
Standalone PV panel	4.8
Solar water heater	2.5
PV-T system	2.9

IV. CONCLUSION

The study on the performance of PV-T system has been successfully investigated. The PV-T systems can produce more energy per area than separate solar PV panels or thermal collectors. The PV-T systems can meet the electricity and heat needs of a building, which can significantly reduce CO_2 production on earth. The thermal efficiency of the PV-T using a liquid working fluid has a higher value than using an air working fluid. Moreover, the temperature in the heat absorber area greatly determines the PV-T system's electrical and thermal efficiency. High temperatures (using a cover) will produce more heat energy, but it impacts the reduction of the electrical energy production from the PV panels.

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