Energy and exergy analysis of solar photovoltaic thermal system: experimental and numerical verification

Metin Gül*
Balıkesir University Institute of Science,
Balıkesir, Turkey
Email: metingul@balikesir.edu.tr
*Corresponding author

Ersin Akyüz
Department of Electronic and Automation,
Balıkesir University Vocational School,
Balıkesir, Turkey
Email: eakyuz@balikesir.edu.tr

Abstract: In this study, the electrical and thermodynamic performance of a flat-plate liquid PV/T system was investigated, and the experimental results were verified with a numerical model implemented. The simulation analyses showed that the increasing inlet and ambient temperature had a negative effect on thermal efficiency and the highest thermal efficiency was obtained at 800 W/m² solar radiation. The optical efficiency of the experimental system was verified with the simulation and reported as 45.8% and 47.9%, respectively. Hourly electrical, thermal, and total energy efficiencies obtained hourly on a daily basis were calculated and varied between 12–13.8%, 36.1–45.2%, and 49.1–58.4% respectively on daily basis. The hourly exergy analyses were also carried out and the results showed that the exergy efficiencies changed between 13.8–14.32%. The annual total thermal and electricity energy outputs were calculated as 1,912 kWh and 556.8 kWh respectively.

Keywords: photovoltaic thermal system; PV/T; solar energy; energy; exergy; life-cycle cost.


Biographical notes: Metin Gül received his BS in Electric-Electronics Engineering from Balıkesir University, Balıkesir, in 2016, and MSc in Electric-Electronics Engineering from Balıkesir University, Balıkesir, in 2019. His current research interests include renewable energy sources.

Ersin Akyüz is an Assistant Professor at the Department of Electronic and Automation, Balıkesir University vocational school, Balıkesir, Turkey. He graduated from the Istanbul Technical University in 1996. He received his MSc in Gazi University, Department of Electric-Electronic in 2003. He received his PhD in Balıkesir University Mechanical Engineering in 2010. His research interests are renewable energy, hydrogen energy, and IoT distributed systems.
1 Introduction

Nowadays, global warming, which is mainly attributed to the combustion of fossil fuel, has become one of the most serious problems threatening our future. The most effective way to combat this problem is to utilise more renewable energy sources instead of fossil sources. Today, the widespread utilisation of solar energy sources, which are abundant and have clean characteristics, stands out for the solution of these problems and is used as a global energy source around the world (Li et al., 2019). Due to the reduction in costs, the use of solar energy applications is rapidly becoming widespread in the world. By the end of 2018, the installed power capacity and thermal capacity of photovoltaics were 509.3 GW and 480 GW, respectively, in the global market (SPE, 2019).

A PV/T consists of a PV module and an integrated solar thermal collector using air or water as fluid for cooling the module. The conversion rate of solar energy to electrical energy is low in PV systems; hence, this causes heating in PV cells. PV/T systems increase the amount of useful energy by absorbing waste heat from the system through cogeneration. The idea of photovoltaic thermal systems to provide heat and electrical energy together and increase the efficiency of PV systems started to attract the attention of researchers towards the end of the 1970s. These systems were first proposed by Wolf in 1976, who was a pioneer for other researchers (Wolf, 1976). PV/T modules have a structure that can be used to preheat air or liquid fluids in industrial and domestic areas. In practice, the liquid collector is more effective and practical than the air collector, since the temperature change due to fluctuations in solar radiation levels in liquid is the less than in air (Tonui and Tripanagnostopoulos, 2007).

Many researchers have conducted theoretical studies about numerical models which include physical models of PV/T systems and evaluated system performance. According to these studies evaluating the performance of PV/T systems under different operating conditions and with different components, the total efficiency of PV/T varies between 47.4% and 80% (Khelifa et al., 2015; Bergene and Lovvik, 1995). Additionally, studies supporting numerical studies with experimental performance analyses involving building-integration (Chow et al., 2009), collectors with and without glass and selective coatings (Matuska, 2014), with improved laminated absorber (Singh et al., 2019), with low emissivity coatings (Touafek et al., 2014), sheet and tubes (Singh et al., 2019; Ibrahim et al., 2011), air PV/T (Sopian et al., 1996), and commercial modules (Herrando and Markides, 2016) are also available in the literature. Some of the studies evaluating PV/T efficiency reported that the electrical efficiency of PV/T systems at appropriate fluid temperatures is higher than PV systems (Sakhr et al., 2013) and the total efficiency varies between 54.6% and 74.1% (Sakhr et al., 2013; Fudholi et al., 2014).

The sheet and tube model are one of the most widely used water-based PV/T configurations. An insulated air gap exists between the glass cover and the encapsulation, which is used to reduce radiation losses in the collector and reduce transmission losses from the absorbent plate to the collector. The heat caused by the absorbed solar energy is transferred to the outside of the collector with copper pipes on the absorber plate fixed to the PV cells with an adhesive, thus decreasing the PV/T cell temperatures (Ibrahim et al., 2011).

The effects of glass cover, fluid type, mass flow rate, and absorptive properties on the efficiency of PV/T collectors were analysed and it was reported that the thermal efficiency ranged from 45% to 70% (Dalvand et al., 2012).
Although there are studies about the energy analysis in PV/T systems, a limited number of exergy analyses exist in the literature. Exergy analysis evaluates the quantity and quality of the energy and enables system performance analysis to be performed more accurately. Joshi et al. (2009) investigated the performance characteristics of PV and PV/T systems based on energy and exergy efficiency. It was found that the energy and exergy efficiency of the PV/T system was higher than that of the PV system. In another study, PV/T energy efficiency ranged between 55% and 62% and the change in exergy efficiency was between 12% and 14%. In addition, performance analyses of PV/T systems with different PV technologies were completed for use in PV/T exergy analyses. Accordingly, the energy and exergy efficiencies of PV/T systems with monocrystalline PV cells were found to be higher (Ibrahim et al., 2014).

The number of economic studies performed about PV/T systems regarding the payback period is excessive; however, studies investigating the cost of energy with the life-cycle cost methodology are limited. Guarracino et al. performed a techno-economic analysis of a PV/T system in climatic conditions in Larnaca and London and determined that energy costs vary greatly according to location as a result of life-cycle cost analysis. According to the obtained electrical, thermal and total energy type, unit energy costs are 1.29 €/kWh, 0.34 €/kWh, 0.68 €/kWh, respectively, for Larnaca and 0.46 €/kWh, 0.76 €/kWh, 0.50 €/kWh, respectively, for London (Guarracino et al., 2016).

In this study, thermodynamic and electrical performances of a PV/T system were examined with energy and exergy analyses. Data such as radiation, temperature, mass flow rate, current and voltage were measured and collected during June 2017–September 2018 for a PV/T system built-in Balikesir University Campus (39° 39' 11.873" N 27° 53' 25.231" E). The experimental electrical, and thermal efficiency values, PV/T cell temperature, energy and exergy efficiencies were calculated and verified with a numerical model. In addition, an economic analysis was carried out and the costs of energy values were calculated with respect to the energy type. The effects of variables such as interest and lifetime on the cost of energy were also investigated. In particular, interest rates that include periodic variability, such as in Turkey, are vital as an important variable for future investment strategies of investors. PV/T studies are included in the literature as experimental or modelling. Verification studies with experimental and numerical models are more limited and are usually carried out with package software such as TRNSYS. In this context, this study aims to compensate for the lack of literature in this field through both experimental and modelling studies.

2 Material and method

2.1 System design

The experimental system [Figure 1(b)] was built in Balikesir/Turkey utilising two identical PV/T panels (39° 39’ 11.873” N 27° 53’ 25.231” E) with a tilt angle of 30 degrees. The experiments were implemented during June 2017–September 2018. The PV/T system was installed on a light-coloured tile surface and has a high surface reflectance coefficient than the standard albedo coefficient (0.2). This provided to increase the receipt of reflected radiation on PV module foreground surfaces.

The parameters measured by the mass flow rate of water were between 0.015 kg/s to 0.076 kg/s in this period. Two PV/T modules were used in the system and each module
(1.64 m × 0.87 m with 1.222 m² active area) is composed of 72 numbers of cells. The electrical output power of each panel is 200 Wp with the 5.43 maximum power current and 36.8 maximum power voltage and the thermal power rating is 680 W. The electrical system consists of a charge regulator (45 A), battery (24 V–200 Ah) and an inverter (1,500 W) for feeding loads. A storage tank (100 L) and a pump were used to circulate the fluid at different mass flow rates.

Figure 1   (a) Principle scheme (b) Experimental scheme of the PV/T system (see online version for colours)

Data such as current, voltage, temperature, global irradiance, and wind speed were measured from the points shown in Figure 1(a). The thermocouples (PT100 and J type) were used for measuring the ambient, cell, and collector inlet and outlet temperatures. The cell temperature of the PV/T was measured from the front surface by J type thermocouple. A pyranometer (Kipp and Zonen CMP11 model) was used to measure the incident solar radiation. The water flow rate was calculated with the flow metre (LZB 15 SL (0-250L/h). The output current was measured with the current sensor (ASC712). A data logger (Campbell Scientific CR1000) was used to record the data with the desired time periods and accuracy. The CR1000 datalogger has 16 analogue single-ended inputs (eight differentials), and the measurements were recorded at desired intervals with the help of connected sensors. Data were measured in 1, 10, and 60-minute intervals and stored in the datalogger memory.

2.2 Mathematical model of the PV/T system

The electrical efficiency ($\eta_e$) is calculated with respect to the maximum power point voltage ($V_{MP}$), current value ($I_{MP}$) and the amount of radiation on the surface area.

$$
\eta_e = \frac{P_{el}}{I_F A} = \frac{V_{MP} I_{MP}}{I_F A}
$$

(1)
Thermal efficiency changes with the mass flow rate ($\dot{m}$), the difference between the inlet and outlet temperatures of the fluid ($T_o - T_i$), the solar radiation ($I_T$), and specific heat ($C_p$).

$$\eta_t = \frac{Q_u}{I_T \cdot A} = \frac{\dot{m} \cdot C_p \cdot (T_o - T_i)}{I_T \cdot A} \quad (2)$$

In order to compare the experimental system, a numerical model of the PV/T which includes the physical, electrical and thermal properties was created. The PV/T one-dimensional steady-state model with a flat-plate collector was modelled using the Hottel-Whillier equations for thermal analysis. Heat losses are considered in the thermal performance calculations of the PV/T. These losses depend on variables such as solar radiation intensity, wind speed, ambient temperature, structure of the collector, transparent covering properties, radiation emission and absorption value of the absorber surface, thermal conductivity coefficient, thickness, type and thickness of the insulation material (Duffie and Beckman, 2013).

Steady state thermal efficiency of PV/T collectors ($\eta_t$)

$$\eta_{th} = \frac{Q_u}{I_T} \quad (3)$$

$$Q_u = A \cdot F_R \left[ S - U_L \left( T_i - T_o \right) \right] \quad (4)$$

$$U_L = U_i + U_b + U_e \quad (5)$$

Total heat losses consist of bottom, top and edge surfaces in the collector.

$F_R$ collector flow rate factor

$$F_R = \frac{\dot{m} \cdot C_p}{A \cdot U_L} \left[ 1 - e^{\frac{A \cdot U_L \cdot F}{\dot{m} \cdot C_p}} \right] \quad (6)$$

$F'$ collector efficiency factor

$$F' = \frac{1}{U_L} \left[ \frac{1}{D + (W - D)F} + \frac{1}{W \cdot J_{PV/4}} + \frac{1}{\pi D h_{fl}} \right] \quad (7)$$

$F$ is the fin factor

$$F = \frac{\tanh \left( \frac{\tanh \left( M \frac{W - D_b}{2} \right)}{M \frac{W - D_b}{2}} \right)}{M \frac{W - D_b}{2}} \quad (8)$$

Using all these equations, the thermal efficiency expression can be found from the equation given in equation (9)

$$\eta_t = F_R (\alpha \tau) - F_R U_L \frac{T_o - T_i}{I_T} \quad (9)$$
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\( T_{pm} \) is the average temperature of the absorber plate and is used for the electrical efficiency calculation in equation (10).

\[
T_{pm} = T_{in} + \left( \frac{Q_{in}/A_s}{U_L F_R} \right)(1 - F_R)
\]  

The equation given by Radziemska (2003), with electrical efficiency changes depending on the PV temperature, is shown in equation (11); \((\beta = 0.0045)\)

\[
\eta_{el} = \eta_0 \left[ 1 - \beta (T_{pm} - T_{ref}) \right]
\]  

The amount of electrical power to be obtained from the PV/T panel is given in the following equation.

\[
P_{el} = \eta_{el} A_s J_T
\]  

2.3 Exergy analysis

Exergy analysis is based on the second law of thermodynamics where the general exergy balance can be expressed in proportional form, if the effects arising from kinetic and potential energy changes are neglected (Fudholi et al., 2014).

\[
\sum E_{xin} - \sum E_{xout} = \sum (E_{xth} + E_{xel})
\]  

\( T_s \) is the temperature of the sun and taken as 5778 K. \( E_{xin} \) is exergy input and can be written as:

\[
E_{xin} = A_s J_T \left[ 1 - 4 \left( \frac{T_o}{T_s} \right) + \frac{1}{3} \left( \frac{T_o}{T_s} \right)^4 \right]
\]  

Thermal and electrical exergy

\[
E_{xth} = Q_o \left[ 1 - \left( \frac{T_o + 273}{T_s + 273} \right) \right]
E_{xel} = \eta_{el} A_s J_T \left[ 1 - 4 \left( \frac{T_o}{T_s} \right) + \frac{1}{3} \left( \frac{T_o}{T_s} \right)^4 \right]
\]  

2.4 Economic analysis

The total life-cycle cost (TLCC) method, which is used to compared the energy costs of technologies with different cost structures, is preferred compared to economic analysis. TLCC analysis attempts to calculate the cost of delivering a service during the whole period of the project, rather than comparing only the initial capital costs or operating costs. The final cost (\$/kWh) is estimated independent of the technology used to deliver the electricity. In this method, all the costs (capital cost (CC), operating and maintenance costs (OMC), repair and replacement costs (RRC) and salvage value (Salv) that will occur during the system lifetime, are considered based on the time value of money (Akyuz et al., 2010).

\[
TLCC = \sum CC + \sum OMC + \sum RRC - \sum Salv
\]
The present value for the OMC that will occur during the entire lifetime of the system represents the annual OMC and is taken as 1% of the total capital cost in this study. Depending on the lifetime of the system components, replacement costs are reduced to their present value. The salvage value is taken as one-tenth of the capital cost in calculations of present value for the total salvage value. After the total cost is calculated with equation (17)

\[ ALCC = \frac{(TLCC)i}{1-(1+i)^{-N}} \]  

Cost of energy is calculated with equation (18)

\[ COE = \frac{ALCC}{E} \]  

Lifetime and interest rates are important variables that affect the cost of energy. In order to determine the effect of these variables on the cost of energy, the cost of energy is calculated by taking interest values varying between 2–20% and the lifetime values of 20, 25, and 30 years. PV/T system thermal energy and electricity components include principal and operational maintenance costs, scrap prices, and separate heating and electrical energy total lifetime costs.

### 2.5 Simulation model

In order to implement numerical model simulation software was used (Simulink, 2020). Theoretical model includes numerical expressions of the PV/T system. The output variables such as electrical and thermal efficiency, energy and exergy amounts, etc. are calculated with respect to meteorological input data. Many different blocks in the software provides to calculate variables such as fin factor, collector flow rate factor and heat losses. Thus, the desired output variables can be calculated hourly, daily, monthly, and yearly using hourly input variable.

The input variables interest rate, N the lifetime, and the annual electrical and thermal energy amounts are used to calculate the energy cost for the economic model. In the numerical model, the costs of energy for thermal and electrical energy are calculated separately.

### 3 Results and discussion

The hourly data were measured and stored by the data logger between the dates of 10/08/2017 and 31/07/2018. The thermal and electrical energy produced for per m² PV/T modules were calculated as 783.6 kWh and 228.2 kWh with the mathematical model, respectively. Monthly electrical and thermal energy amounts respect to solar inclined radiation is given in Figure 2.

In order to perform verification between the numerical model and experimental system, collector inlet and outlet temperatures, electrical, and thermal energy and exergy efficiencies were calculated and compared with the experimental results. Hourly radiation and ambient temperature measurement data for the specified dates (06.06.2018–24.06.2018) were used for the verification.
Collector inlet-outlet temperatures measured between the given dates were compared with the results obtained with the mathematical model and while the highest temperature measured at the output of the experimental system at a mass flow rate of 0.033 kg/s was 50.2ºC, it was calculated as 53.7ºC with the mathematical model.

The daily total thermal and electrical energy values obtained from the system were calculated and compared with the mathematical model in Figure 3. As the total thermal energy amount produced in the experimental system was 68.6 kWh between the given dates, it was calculated as 71.1 kWh with an error rate of 3.6% in the numerical model. While heat losses arising from the structure of the collector are taken into consideration in the numerical model, there are also insulation losses outside the collector in the experimental system. The total electrical energy value produced in the experimental system within the given date range is 19.5 kWh in the simulation model, it was calculated as 19 kWh with an error rate of 2.6%.

Thermal efficiencies were calculated when different radiation, ambient temperature, and fluid inlet temperatures are equal (\(T_{\text{in}}-T_{\text{a}}/T_{\text{r}} = 0\)) at constant mass flow rate. The analysis was carried out between 20–35ºC fluid inlet and air temperature and 200–800 W/m² radiation values in the numerical model. It was observed that increasing fluid inlet and the ambient temperature had a negative effect on thermal efficiency and maximum thermal efficiency values were obtained at 800 W/m² irradiation value.
The analysis was repeated for \((T_{ir}-T_a = 5\degree C)\) in the graphic in Figure 4. Comparing the efficiency values obtained is given below. Accordingly, it was observed that the increase in radiation intensity and inlet collector inlet temperature decreased the thermal efficiency.

**Figure 4** (a) Variation of thermal efficiency as a function of the ratio \((T_{in}-T_a/\eta = 0)\) according to varying solar radiation (b) Variation of thermal efficiency as a function of the ratio \((T_{in}-T_a/\eta = 5)\) according to varying solar radiation (see online version for colours)

The change in thermal efficiency was calculated with both experimental and simulation data depending on \((T_{ir}-T_a/\eta)\) on a daily basis and is given in Figure 5 for comparison. Thermal efficiency was calculated by the simulation under the same conditions. As the optical efficiency value obtained for the experimental system was 45.8%, in the simulation this value was calculated as 47.9%.

**Figure 5** Comparison of experimental and simulation thermal efficiencies as a function of the ratio \((T_{ir}-T_a)/\eta\) (see online version for colours)

The hourly PV/T cell temperature variation with respect to radiation and ambient temperature on a daily basis is shown in Figure 6(a). While the incident solar radiation
and ambient temperature change between 431–1,142 W/m² and 18–30.75°C, respectively, the PV temperature changed between 38.88°C and 56°C and produced electrical, thermal and total energy amounts were calculated as 68.6–176 Wh, 190.3–603 Wh, and 258.9–779 Wh, respectively. It was found that the increase in PV/T cell temperature led to decrease in both electrical efficiency and electrical energy amount produced.

Figure 6  (a) The average hourly solar radiation, temperatures and amount of energy on 8th of June (b) Changes in energy and exergy efficiencies and outlet temperature on the 8th of June (see online version for colours)

The performance of the PV/T system was determined by the combination of the hybrid system components. It consists of electrical and thermal efficiency and total efficiency calculated from the sum of both efficiencies. The hourly total efficiency of the PV/T system are shown in Figure 6(b) on a daily basis for the mass flow rate of 0.033 kg/s. The electrical, thermal, and total efficiencies were calculated as 12–13.8%, 36.1–45.2%, and 49.1–58.4%, respectively.

The exergy efficiency calculated for a sample day at 12:00 am. While the inclined solar radiation, ambient temperature and flow rate were 835 W/m², 24.65°C and 0.0277 kg/s, inlet and outlet temperatures were measured as 26.169°C and 29.611°C, respectively and the exergy efficiency of the system was calculated as 13.8%.

Figure 7  Comparison of exergy efficiencies in experimental and simulation systems on the 14th of June (see online version for colours)
The hourly energy and exergy efficiencies were compared on a daily basis in Figure 6(b). While the ambient and outlet temperatures change between 18–30.75°C and 26.21–41.21°C, the total energy and exergy efficiencies were calculated as 49.1–58.4% and 13.8–14.32%, respectively. The hourly experimental exergy efficiency is compared with the numerical model in Figure 7. It was found that the experimental and numerical efficiency varied between 13.7–15.24% and 13.77–14.77%, respectively.

Economic analysis of the PV/T system was carried out with the TLCC method using thermal, electrical and total energy costs separately. The sensitive analysis was also carried out and the effects of the change in interest rate (2–20%) and lifetime (20, 25 and 30 years) on energy cost was calculated. The cost of thermal energy was calculated for 20, 25 and 30 years with respect to varied interest rates as $0.082–0.172, $0.078–0.171 and $0.075–0.170, respectively. It was found that the variation in unit interest rate increases the cost of thermal energy by rates of 2.76%, 2.86% and 2.95%, respectively, for 20, 25, and 30 years lifetime. Similarly, the costs for electrical and total energy were calculated in the same way. The cost of electrical energy was calculated for 20, 25 and 30 years with respect to varied interest rates between $0.389–0.642, $0.356–0.636 and $0.403–0.638, respectively. It was found that the variation in unit interest rate increased the cost of thermal energy by rates of 7.8%, 8.6%, and 7.3%, respectively, for 20, 25, and 30 years lifetime. The cost of total energy was calculated for 20, 25 and 30 years with respect to varied interest rate as being $0.112–0.239, $0.103–0.237, and $0.104–0.236, respectively. It was found that the variation of unit interest rate increased the cost of thermal energy by rates of 3.8%, 4.08%, and 4.05%, respectively, for 20, 25, and 30 years lifetime. The variation of energy cost depends on lifetime and interest rate was given in Table 1.

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<td>30</td>
<td>0.403</td>
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### 4 Conclusions

In this study, in order to perform verification, an experimental system was compared with the numerical model implemented. Comprehensive exergy and energy analyses of the PV/T system built-in Balikesir/Turkey were carried out and beyond the energy and exergy analysis, the cost of energy calculations was completed with the economic analysis. These are the conclusions drawn from the current study:

- The annual amounts of electrical and thermal energy produced for per m² PV/T module were calculated as 228.2 kWh and 783.6 kWh, respectively.
- The total thermal energy value produced in the experimental system was 68.6 kWh between the given dates; in the simulation model, it was calculated as 71.1 kWh with an error rate of 3.6%.
The total electrical energy value produced in the experimental system within the given date range was 19.5 kW. It was calculated as 19 kWh with an error rate of 2.6% in the simulation model.

It was observed that increasing fluid inlet and the ambient temperature had a negative effect on thermal efficiency and maximum thermal efficiency values were obtained at 800 W/m² irradiation values.

The optical efficiency value obtained for the experimental system was 45.8%; in the simulation this value was calculated as 47.9% with an error rate of 4.5%.

The hourly change in electrical, thermal, and total efficiency of the PV/T system at a mass flow rate of 0.0333 kg/s was calculated. Accordingly, the efficiencies vary between 12–13.8%, 36.1–45.2% and 49.1–58.4%, respectively.

Energy and exergy efficiencies were compared, and it was determined that the energy efficiency values between 49.1–58.4% are higher than the exergy efficiency with values between 13.8–14.32%.

Although many studies have been completed in water-based PV/T system, still some obvious opportunities are existing for further developing this technology, such as, nanofluid and PCM-based PV/T. The effect of the climatic changes above long term dynamic energy performance of the PV/T hybrid systems. The optimising of the structural and geometrical parameters of the existent PV/T configurations to raise energetical performance.

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