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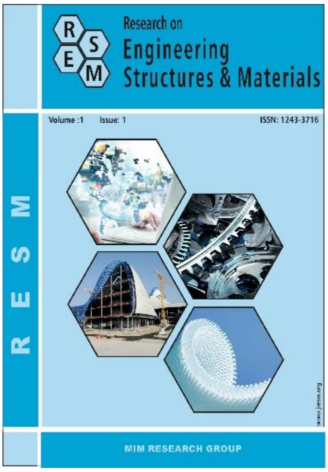

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Research Article

A comparative study on the energetic- exergetic and economical performance of a photovoltaic thermal system (PVT)

Canan Kandilli[a]

Department of Mechanical Engineering, Uşak University, Uşak, TURKEY

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Abstract

In this experimental study, it is aimed to present a comparative study on the energetic-exergetic and economical performance of the PVT system. A new and easy-handle approach has been also developed to assess the exergetic performance of a PVT system. Economical evaluation of both PV and PVT systems has been also performed by NPV method. Useful energy rate, surface temperature, electrical energy and overall energy efficiency, exergy efficiency, exergy destruction values of PV and PVT systems have been compared. It was found that the electrical efficiency, overall energy efficiency and exergy efficiency of PVT system vary between 0.10 and 0.13; 0.26 and 0.54 and 0.10 and 0.12 respectively. It is found that the exergy and energy efficiency values of the PVT system are greater than the exergy and energy efficiency values of the PV system. It is calculated that the PVT system has considerably short payback time after 8 years of operation; while the payback period of PV was found as 16 years under the same meteorological conditions.

1. Introduction

The conversion efficiency of photovoltaic cells is relatively low, usually in the range of 10–20% for commercially available silicon cells. More than half of the solar radiation, collected with considerable effort and investment, is converted to thermal energy and then rejected to the environment. A well-known way to achieve a better overall efficiency is cogeneration: capturing the waste heat as well and using it as an additional energy product. This can be achieved with photovoltaic/thermal (PVT) collectors that contain a heat exchanger behind the PV cells to collect the heat rejected from the cells [1]. The concept of PVT has been used and discussed for more than three decades by various researchers both experimentally and numerically. During the 1970s, the research on PVT started, with the focus on PVT collectors, with the main aim of increasing the overall energy efficiency [2].

PVT idea is based on the utilizing both a PV and a thermal system together. The aim of PVT systems is not only to cool the system, is to utilize the heat emerged on the system as well. There are many theoretical and experimental studies on air or water cooling application for PVT system in the literature [3-17]. Chow et al. [8] developed energy models for a building-integrated photovoltaic/water-heating system. They showed that the photovoltaic/ water-heating system is having much economical advantages over the conventional photovoltaic installation. They also observed that the system thermal performance under natural water circulation is better than the pump-circulation mode. They found that the year-round thermal and cell conversion efficiencies were found

*Corresponding author: canan.kandilli@usak.edu.tr
[a] orcid.org/0000-0001-7159-4174
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respectively 37.5% and 9.39% under typical Hong Kong weather conditions. Pei et al. [17] proposed heat-pipe photovoltaic/thermal (HP-PV/T) collector. They found the daily thermal efficiency, electrical efficiency, total PVT efficiency and primary-energy-saving efficiency as 41.0–48.0, 10.0–11.2, 47.0–53.3 and 57.0–63.0% for the system using the collector with the tube space of heat pipes at 80 mm, respectively.; while the daily thermal efficiency, electrical efficiency, total PVT efficiency and primary-energy-saving efficiency were 39.0– 46.0, 9.0–11.0, 45.0–51.0 and 53.0–60.0% for the system using the collector with the tube space of heat pipes at 140 mm, respectively.

Although numerous studies exist on the energy performance of PVT systems, there are very limited studies on the exergetic assessment. It is essential to analyze the quality of energy as well as its quantity. Exergetic analysis of any system could provide more accurate results to evaluate the system performance. Chow et al. [18] carried out a study of the appropriateness of glass cover on a thermosyphon-based water-heating PVT system. They found that a glazed PVT system is suitable to maximize the quantity of either the thermal or the overall energy output. On the other hand, from the exergy analysis point of view, the increase of PV cell efficiency, packing factor, water mass to collector area ratio, and wind velocity are found favorable to go for an unglazed system, whereas the increase of on-site solar radiation and ambient temperature are favorable for a glazed system. Tiwari et al. [19] observed that the daily overall thermal efficiency of the integrated photovoltaic thermal solar system increases with increase constant flow rate and decrease with increase of constant collection temperature. They also investigated the system exergetically. Dincer et al. [20] performed a detailed review of photovoltaic and photovoltaic thermal systems on the basis of its performance based on electrical as well as thermal output. The performance analysis has been also discussed including all aspects, e.g., electrical, thermal, energy, and exergy efficiency. Sarhaddi et al. [21] presented a detailed energy and exergy analysis to calculate the thermal and electrical parameters, exergy components and exergy efficiency of a typical PVT air collector. They found that the thermal efficiency, electrical efficiency, overall energy efficiency and exergy efficiency of PV/T air collector is about 17.18%, 10.01%, 45% and 10.75% respectively for a sample climatic, operating and design parameters. Saidur et al. [22] gave a place to exergy analysis of PVT system in their comprehensive literature review including exergy modelling. Ozturk et al. (2012) performed an energy, exergy and Life Cycle Assessment (LCA) analysis of a Flat-Plate (FP) collector, a Photovoltaic (PV) system and a Photovoltaic-Thermal (PVT) collector. They found that instantaneous energy, daily energy and exergy efficiency of the FP collector, the PV system and the PV/T collector vary between 53-61%, 19-30%, 23-37% and 56-74%, 11-15%, 21-34% and 2-7%, 6-22% and 8-16%, respectively [23]. Tiwari and Barnwal (2009) carried out the performance analysis of a hybrid photovoltaic-thermal (PV/T) greenhouse air heater and dryer. They observed that exergy efficiency of the greenhouse air heater is less than the thermal efficiency, and exergy efficiency with load is lower than that of without load as expected [24]. Kumar and Tiwari (2009) presented the thermal analysis of a new design of hybrid photovoltaic/thermal (PV/T) active solar distillation system. They concluded that the average annual exergy efficiency of hybrid active solar still is higher than passive solar still almost by 25%, while the energy efficiency is lower by 24% [25]. Tiwari et al. (2009) studied on the Energy Pay Back Time (EPBT) of Hybrid Photovoltaic-Thermal (HPVT) air collector based on exergy analysis for composite climate of New Delhi. They also evaluated the exergy metrics namely Electricity Production Factor and Life Cycle Conversion Efficiency in addition to EPBT by using exergetic output. They concluded that that EPBT of HPVT air collector without balance of system based on exergy and energy output is about 10 years and 2 years, respectively, for single fan operation of the HPVT air collector [26].

Actually, there are many different active and passive cooling methods for enhancing PV module efficiency. While hybrid PV/TE system integrating heat sink [27], Hybrid micro-channel solar cell/module [28], using nanofluid [29], using PCM [30], direct liquid-immersion cooling [31], natural circulation of water in a flat-box absorber [32], using hybrid microchannel with nanofluid [33-35], using microchannel heat sink with nanofluid could be listed as passive cooling methods; jet impingement , water spraying, using ferrofluid and magnetic field and Jet array nanofluids impingement could be considered active cooling system in the literature [36-39].

However, comparative studies including exergetic assessment on PVT systems are very limited in the literature. In the present study, a new and easy-handle approach has been proposed to assess the exergetic performance of a PVT system; it is aimed to present a comparative study on the energetic- exergetic and economical performance of a PVT system consisting monocrystalline silicon solar cells and a copper plate with copper tubes on the back for water heating. Economical evaluation of both PV and PVT systems has been also performed by NPV method. There is not any study on comparison of PV and PVT systems by NPV method in the literature. The experiments have been conducted at Usak University, Department of Mechanical Engineering, in March, 2012. The data have been employed to determine electrical and thermal performance of the experimental (PVT) and the control (PV) systems. Useful energy rate, surface temperature, electrical energy and overall energy efficiency, exergy efficiency, exergy destruction values of PV and PVT systems have been compared. The variation of entropy generation due to surface temperature of PVT system has been examined and discussed. In the first section of the present study, it was given a brief review on PVT systems and explained the aim of the study. In the second section, theoretical aspects and thermodynamic analysis have been represented. Description of the control (PV) and experimental (PVT) systems employed in the study, data used in the calculations and the results of the experiments are covered in "Results and Discussion" as Section 3, while the last section gets conclusions.

2. Thermodynamic Analysis

Solar energy exhibits a spectrum with a very wide range of wavelengths. A certain part of wavelengths of the solar spectrum are converted to electrical energy by PV materials. After the interaction between the materials and solar energy, a great portion of the solar energy is transformed to excessive heat, not to electrical energy. This excessive heat load on the materials affects negatively the crystalline structure of PV and causes to decrease the energy efficiency for both short and the long terms. However, PVT systems provide both electrical and thermal conversion and help to remove this excessive heat load. While this excessive heat load could be utilized as a thermal energy source, the electrical conversion efficiency of the PV can be kept at the desired values. For example, mono-crystalline Si solar cells have been employed in the present study. Mono-crystalline Si solar cells have a spectral response of 400-800 nm wavelength of solar radiation and can convert the solar energy to electricity in this spectral range. Wavelength values outside this spectral range cause the excessive heating load on the Si solar cell. This excessive heat load can be evaluated as a thermal energy source and can be utilized to heat water for building applications.

The first law of thermodynamics deals with the quantity of energy and asserts that energy cannot be created or destroyed. This law merely serves as a necessary tool for the bookkeeping of energy during a process and offers no challenges to the engineer. The second law, however, deals with the quality of energy. The second law of thermodynamics has proved to be a very powerful tool in the optimization of complex thermodynamic systems [23]. In this section, energy and exergy analyses have been modeled, and the NPV method has been explained for the economical analysis.

2.1. Energy Analysis

The overall energy efficiency of a PVT system could be calculated as below:

$$\eta_{pvt} = \eta_{pv} + \eta_{th} \tag{1}$$

The electrical energy efficiency of a PV system can be found as follows:

$$\eta_{pv} = \frac{V_m I_m}{A_{pv} I_t} \tag{2}$$

The thermal efficiency of a PVT system could be defined by following equation:

$$\eta_{th} = \frac{\dot{Q}}{A_{pv} I_t} \tag{3}$$

The useful thermal energy of any water heating system could be easily calculated as below:

$$\dot{Q} = \dot{m} C_p (T_{out,water} - T_{in,water}) \tag{4}$$

2.2 Exergy Analysis

Irreversibility in the system, in other words, the destruction of exergy can be presented as follows [40]

$$\Sigma \dot{E}x_{in} - \Sigma \dot{E}x_{out} = \Sigma \dot{E}x_{dest} \tag{5}$$

In the present study, a new and easy-handle approach has been also developed to assess the exergetic performance of a PVT system by defining the inlet exergy rate ($\dot{E}x_{in}$) and the outlet exergy rate ($\dot{E}x_{out}$) as below. $\dot{E}x_{in}$ consists of the exergy rate of solar and exergy rate of inlet water and $\dot{E}x_{in}$ could be presented as follows:

$$\dot{E}x_{in} = \dot{E}x_{solar} + \dot{E}x_{mass,in} \tag{6}$$

The outlet exergy rate ($\dot{E}x_{out}$) can be defined as the sum of the electrical exergy rate from the PV part and the exergy rate of outlet water.

$$\dot{E}x_{out} = \dot{E}x_{mass,out} + \dot{E}x_{pv} \tag{7}$$

The exergy rate of solar energy could be found as following equation:

$$\dot{E}x_{solar} = \psi_{solar} I_t A_{pv} \tag{8}$$

The maximum efficiency ratio ψ_{solar}, can be calculated as follows:

$$\psi_{solar} = 1 + \frac{1}{3}\left(\frac{T_0}{T}\right)^4 - \frac{4}{3}\left(\frac{T_0}{T}\right) \tag{9}$$

where T was taken to equal the solar radiation temperature with 6000 K in exergetic evaluation given by Petela [41].

Inlet and outlet water exergy rates can be found as following equations [23]:

$$\dot{E}x_{mass,in} = \dot{m}_{in}\, \psi_{in} \tag{10}$$

$$\dot{E}x_{mass,out} = \dot{m}_{out}\, \psi_{out} \tag{11}$$

where ψ_{in} and ψ_{out} are specific exergy values for inlet and outlet water respectively and calculated as follows:

$$\psi_{in} = (h_{in} - h_0) - T_0(S_{in} - S_0) \tag{12}$$

$$\psi_{out} = (h_{out} - h_0) - T_0(S_{out} - S_0) \tag{13}$$

The electrical exergy output of PV part of the system could be calculated as follows:

$$\dot{E}x_{PV} = \dot{W} = \eta_{pv} I_t A_{pv} \tag{14}$$

The exergy (the second law) efficiency can be found as below:

$$\varepsilon = \frac{\dot{E}x_{output}}{\dot{E}x_{input}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{input}} \tag{15}$$

The entropy generation rate can be expressed as follows;

$$\dot{S}_{gen} = \frac{\dot{E}x_{dest}}{T_0} \tag{16}$$

where T_0 is dead state temperature.

2.3. Economical Analysis

Net Present Value (NPV) is one of the methods that allow analysing the economic aspects of an engineering system. It is possible to calculate the present value of all annual capital expenditures and savings by NPV methods during the life time of a project. Net present value (NPV) is the sum of all the current values (costs are shown negative, and net savings are shown as positive) is obtained. If NPV is positive then the project is accepted, otherwise application of the project is cancelled. NPV is calculated by the following formulas:

$$NPV = \sum_{i=1}^{n} (B - C)_i \, a_i \tag{17}$$

$$a = \frac{1}{(1+i)^p} \tag{18}$$

"a" is net present value factor, B is gain, p is period, i is discount rate in the equation given above.

3. Results and Discussion

An experimental (PVT) and a control (PV) system chosen the same PV material have been established at Usak University, Department of Mechanical Engineering. Energy and exergy analyses have been carried out for both experimental and control systems. The systems fixed at the same tilt angle (38º) and oriented the same direction have been tested under the same meteorological conditions, during March, 2012. While the inlet and outlet water temperatures, water mass flow rate, ambient temperature, global solar irradiance and temperature on the surfaces of PV and electrical measurements have been recorded for the experimental PVT system; global solar irradiance, surface temperature and electrical data have been collected for the control PV system simultaneously. The sixty-four data have been obtained and employed to compare the electrical and thermal performance of the systems. Properties and characterization of PV modules employed in the present study are presented in Table 1. In the construction of PVT, the thickness of the copper plate fixed to back of the tedlar layer of the PV system is 2 mm and copper pipes welded to the copper plate have a diameter as 8 mm and its length is 23 m. Back of PVT system has been insulated by a layer of glass wool. The photos of the experimental set up including PV and PVT systems can be seen in Fig.1.

Table 1 Properties and characterization of PV modules

I_{sc}/I_{mp} (A)	8.154/7.586
V_{oc}/V_{mp} (V)	37.30/27.18
η_{cell} (%)	15.16
η_{module} (%)	13.69
Area (m^2)	1.617
Front Glass	Transparent, toughened safety glass
Cell Structure	Monocrystalline Si (156 mmx156 mm)
Cell Encapsulation	EVA (Ethylene Vinly Acetate)
Backsheet	Tedlar
Frame	Anodized Aluminum

Extech HD200 type K thermocouples measuring the temperature range from -100°C to 1372°C with measurement error of ±0.15% were utilized to get inlet and outlet temperature of water for the PVT system. Infrared thermometers operating range from -30°C to +550°C, with a measurement error of ±2% have been employed to measure the surface temperatures of the PV and the PVT systems. The current and the voltage values obtained from the PV and PVT system have been read by the solar regulator (Steca PR2020).

(a)

(b)

(c)

Fig 1. The photos of the experimental set up (a) Structure of PVT system, (b) Obtaining data for PVT system, (c) Obtaining data for PV system

Delta OHM HD 2102.2 radiometric probe operating range from 0.1.10-3 W/m² to 2000 W/m² has been used to measure with an uncertainty of ±5% was used to determine the solar irradiance on the surface of PV and the PVT system. The ambient temperature values with ±2°C accuracy have been obtained from the weather station (Davis Vantage Pro2) established on the roof of Mechanical Engineering Department, Usak University. The sixty-four measurements have been collected during the experiments. The results of the analysis according to the data obtained from experiments have been presented as below.

The variation of the useful energy rate (W) obtained from the PV and the PVT systems by incoming solar irradiance (W/m^2) to the surface of the systems are presented in Fig.2. The experiments have been carried out on the roof of Usak University, Mechanical Engineering Department building during March, 2012. Useful energy rates ranged from 44.8 W to 124.4 W and from 83.3 to 584.8 W for PV and PVT systems respectively; while the solar irradiance varied from 323 W/m^2 to 780 W/m^2. Useful energy rates increase by increasing solar irradiance values for both PV and PVT system. It is observed that the useful energy rates of the PVT system are highly greater than the useful energy rates of PV system.

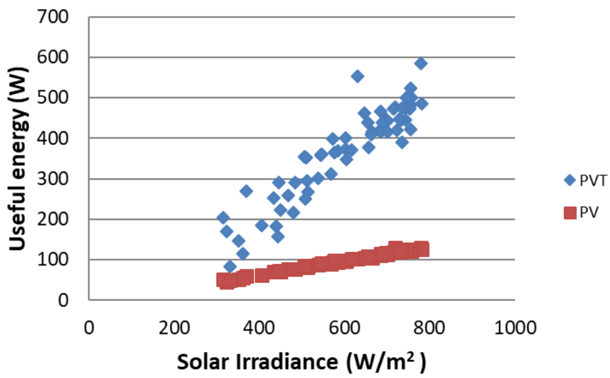

Fig 2. Variation of the useful energy rate (W) obtained from the PV and the PVT systems by solar irradiance (W/m^2)

The variation of surface temperature (K) of PV and PVT systems and ambient temperature (K) are plotted in Fig.3. The surface temperatures of PV and PVT system ranged from 293 to 316 K and 293 to 330 K respectively, while the ambient temperature varied from 283 to 289 K. It is remarkable that the surface temperature of the PVT system is higher than the surface temperature of the PV system. It is estimated that the well-applied insulation on the back of the PVT system causes to decrease the convection losses from bottom side of PVT system. On the other hand, PV module has lower the surface temperature due to convection losses from the bottom of the module. The higher surface temperature of the PVT system could mean that there is still some thermal energy can be transferred to the water. If the heat transfer amount from the solar cell to cooling water could be improved, the surface temperature of PVT could be diminished.

The variation of the electrical energy efficiency of PV and the PVT system and overall energy efficiency of the PVT system due to incoming solar irradiance (W/m^2) to the surface of the systems are given in Fig.4. Electrical energy efficiency values ranged from 0.09 to 0.10 and from 0.10 to 0.13 for PV and PVT systems respectively and the overall energy efficiency values showed results from 0.26 to 0.54; while the solar irradiance varied from 323 W/m^2 to 780 W/m^2. The overall energy efficiency values are in good agreement with the literature [8,17,21,23].

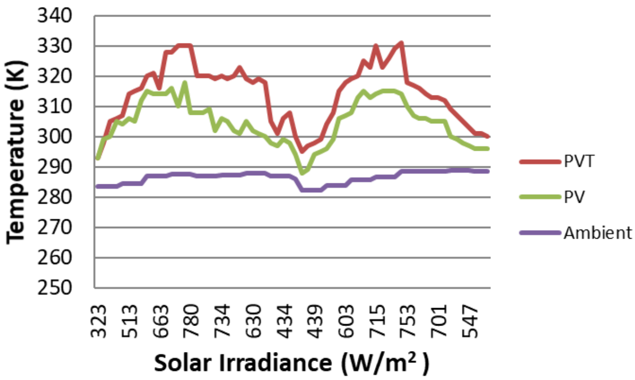

Fig 3. Variation of surface temperature (K) of PV and PVT systems and ambient temperature (K)

The electrical efficiency values of the PVT system are slightly higher than the electrical energy efficiency values of the PV system. In the literature, Tripanagnostopoulos et al. (2002) studied the performance characteristic of PV/water and PV/air systems and compared the electrical efficiency. They found that polycrystalline silisyum (pc-Si) PVT system was more effective as % 3.2 than of the polycrystalline silisyum (pc-Si) PV module [3]. In the present study, it could be confirmed that a PVT application provides the higher electrical energy efficiency than a conventional PV system.

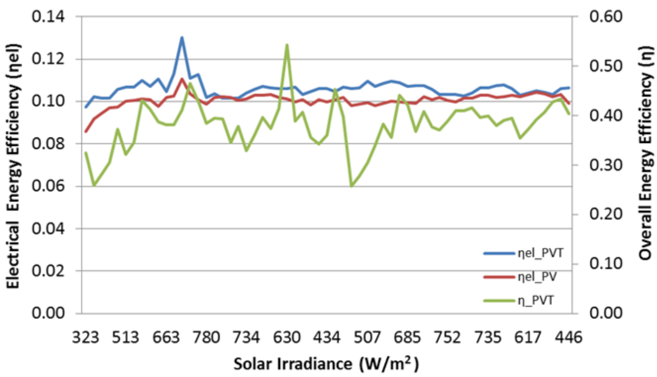

Fig 4. Variation of the electrical energy efficiency of PV and the PVT system and overall energy efficiency of the PVT system due to solar irradiance (W/m^2)

The variation of the exergy efficiency of PV and the PVT system due to incoming solar irradiance (W/m^2) are plotted in Fig.5. The exergy efficiency has taken value from 0.10 to 0.12 and from 0.09 to 0.12 for PVT and PV systems respectively; while the solar irradiance varied from 323 W/m^2 to 780 W/m^2. The exergy efficiency values of the PVT system are slightly greater than the exergy efficiency values of PV system. However, there is not any meaningful difference between the exergy efficiency values of PV and PVT systems.

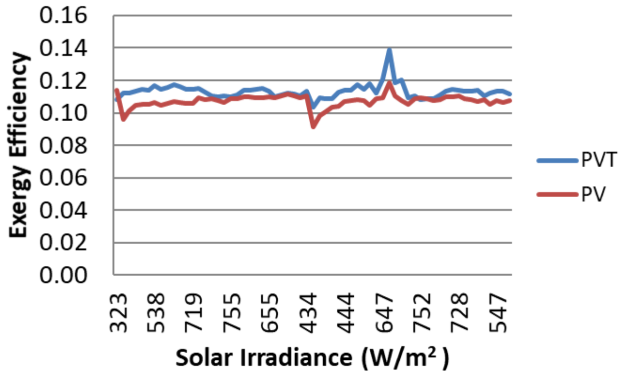

Fig 5. Variation of the exergy efficiency of PV and the PVT system due to solar irradiance (W/m^2)

It is explanatory to examine exergy destruction and entropy generation for the second law of thermodynamics. The difference of the exergy destruction (W) of the PV system and PVT system by solar irradiance (W/m^2) are shown in Fig.6. Difference of exergy destruction rates of PV and PVT systems ranged from 1.98 W to 14.79 W; while the solar irradiance varied from 323 W/m^2 to 780 W/m^2. Exergy destruction rate of PV system is slightly greater than the exergy destruction rate of PVT. However, this difference is not meaningful; when they are compared to high inlet values of solar exergy.

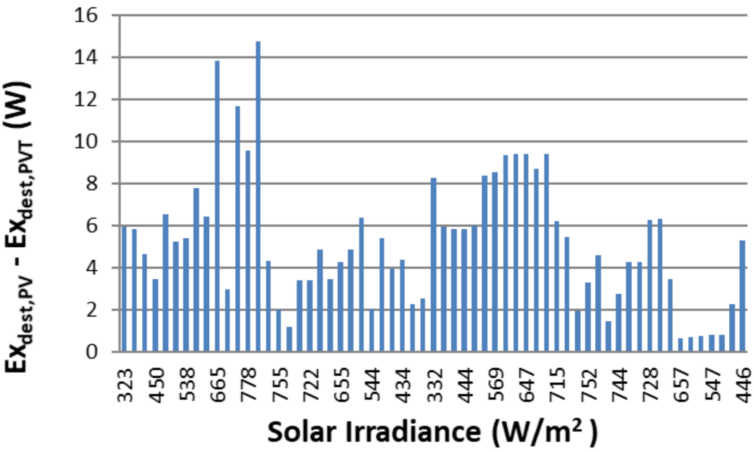

Fig 6. The difference of the exergy destruction (W) of the PV system and PVT system by solar irradiance (W/m^2)

The variation of the entropy generation (W/K) of the PVT system due to surface temperature (K) of PVT system is represented in Fig.7. Entropy generation rates ranged from 1.55 W/K to 3.54 W/K for PVT system; while the surface temperatures of the PVT varied from 293 K to 330 K. Entropy generation rates increase by increasing surface temperatures of PVT system. It could be possible to decrease the entropy generation of PVT system by decreasing surface temperature of PVT system.

Some improvements could be carried out to minimize the entropy generation and maximize the exergy efficiency of the PVT system. Better heat transfer from the solar cells to the copper plate can be supplied by removing the tedlar layer of the PV panel. The surface area of pipes welded to the copper plate can be increased. Pipe diameter, wall thickness of the pipes, material used can be changed to achieve optimum operation condition for future studies. In the present study, the PVT system has been operated at 0.0071 kg/h mass flow rate. The optimum mass flow rate can be investigated to provide maximum the first and the second law efficiencies of the thermodynamics for a future works.

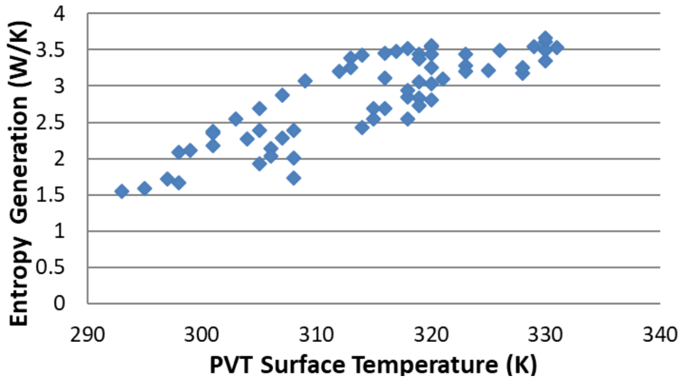

Fig 7. Variation of the entropy generation (W/K) of the PVT system due to surface temperature of PVT system

Table 1. Economical analysis of PVT system by NPV method

Period (Years)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Initial Investment Cost ($)	-1363.0								
Benefits Per Year ($)		202.00	202.00	202.00	202.00	202.00	202.00	202.00	202.00
Maintenance and Repair Costs ($)		-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11
Interest rate	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0,01
Net cash flow ($)		201.89	201.89	201.89	201.89	201.89	201.89	201.89	201.89
Discounted net flow	0.99	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92
NPV		199.89	197.91	195.95	194.01	192.09	190.19	188.30	186.44
		-1163.11	-965.20	-769.25	-575.24	-383.15	-192.97	-4.66	181.78

Economical evaluation of both PV and PVT systems has been also performed by NPV method given as Eq. (17) and (18). The results of economic analysis were shown in Table 2 and Table 3. In the economic analysis, the yearly mean sunshine period was assumed as 7.5 h/day for Usak province and the cost of electricity was accepted 0.20 $/kWh.

Average overall efficiency, produced energy per a year, annual income and investment cost of the PVT system were calculated as 0.32; 801 kWh/a; $ 202 and $1363, respectively. The produced power amounts by the PV and PVT systems were founded as 98.4 W and 363.8 W in average respectively. Maintenance and repair costs for both PV and PVT systems were ignored. It is calculated that the PVT system has considerably short payback time after 9 years of operation; while the payback period of PV was found as 16 years.

Table 2. Economical analysis of PV system by NPV method

Period (Years)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Initial Investment Cost ($)	-1169.00								
Benefits Per Year ($)		83.30	83.30	83.30	83.30	83.30	83.30	83.30	83.30
Maintenance and Repair Costs ($)		-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11
Interest rate	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Net cash flow ($)		83.19	83.19	83.19	83.19	83.19	83.19	83.19	83.19
Discounted net flow ($)	0.99	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92
NPV		82.36	81.55	80.74	79.94	79.15	78.37	77.59	76.82
		-1086.64	-1005.09	-924.35	-844.41	-765.26	-686.89	-609.30	-532.48

Period (Years)	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Initial Investment Cost								
Benefits Per Year	83.30	83.30	83.30	83.30	83.30	83.30	83.30	83.30
Maintenance and Repair Costs	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11
Interest rate	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Net cash flow	83.19	83.19	83.19	83.19	83.19	83.19	83.19	83.19
Discounted net flow	0.91	0.91	0.90	0.89	0.88	0.87	0.86	0.85
NPV	76.06	75.31	74.56	73.82	73.09	72.37	71.65	70.94
	-456.42	-381.11	-306.55	-232.72	-159.63	-87.26	-15.61	55.34

4. Conclusion

Photovoltaic (PV) solar cells can convert a limited fraction of the solar radiation to electrical energy. Depending on the spectral properties of the materials of solar cells, a large proportion of the solar radiation cannot be converted to the electricity and an excessive heat load is occurred in the photovoltaic material. Solar spectra have a wide range of wavelength from 200 nm to 2500 nm, however a solar cell only transform the portion corresponding to the its spectral response ranges into electricity. Electrical conversion efficiency of the solar cell decreases both instantaneously and for long term due to excessive heat load generated on the solar cell and high internal resistance. Furthermore, this effect could damage the material in long term. It is reported in the literature that a temperature rises of 1 °C results in the loss of performance of PV panel by 0.5 % [42]. At this point, photovoltaic thermal (PVT) systems have been designed with the goal of removing this excessive heat. PVT systems produce both electrical and thermal energy by a single module. With this advantage, PVT systems are preferable for supplying energy demand of residential sector, especially.

In the present study, it was aimed to present a comparative study on the energetic-exergetic and economical performance of PVT system based monocrystalline silicon solar cells and a copper plate with copper tubes on the back for water heating.

The main conclusions, which may be drawn from the results of the present study, are listed as follows:

- The useful energy rates (W) of PVT system are considerably greater than the useful energy rates (W) of the PV system.
- It is remarkable that the surface temperature of the PVT system is higher than the surface temperature of the PV system.
- The electrical efficiency values of the PVT system are slightly higher than the electrical energy efficiency values of the PV system. The overall energy efficiency of the PVT system has been reached up to 0.54 and average value was calculated as 0.32.
- The exergy efficiency values of the PVT system are greater than the exergy efficiency values the PV system.
- Exergy destruction values of PV system are slightly higher than the PVT system.
- Entropy generation rates increase by increasing surface temperatures of PVT system. It is possible to decrease the entropy generation of PVT system by decreasing surface temperature of PVT system.
- The PVT system has considerably short payback time after 8 years of operation; while the payback period of PV was found as 16 years.

In the present study, a PVT system has been compared to a conventional PV panel by analysing these systems thermodynamically and economically. It is expected that this study could be very beneficial to researchers and practitioners dealing with the PVT systems to improve their systems efficiently. It is hoped that this study could help to understand the actual performance of PVT systems for building applications.

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Nomenclature

A	area, m^2
C_p	specific heat capacity, J/kgK
$\dot{E}x$	exergy rate, W
I_t	Solar irradiance on the surface, W/m^2
I	current, A
$\dot{m}$	mass flow rate, kg/s
$\dot{S}$	entropy generation rate, W/K
$\dot{Q}$	useful energy rate, W
T	temperature, K
V	voltage, V
$\dot{W}$	work, W
ψ_{solar}	The maximum efficiency ratio
TL	Turkish Liras

Greek letters

ε	exergy efficiency

η energy efficiency

ψ specific exergy

Subscripts

dest destruction

gen generated

in inlet

out outlet

pv photovoltaic

pvt photovoltaic/thermal

solar solar

th thermal

o environment

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