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Research Article

Experimental Analysis of PV/T Collectors Assisted with PCM for Off-Grid Domestic Applications

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Abstract

An experimental study was carried out to examine the efficiency of solar energy in photovoltaic thermal collectors (PV/T) with energy storage. A photovoltaic thermal collector was used to generate both electrical energy and hot water. The effects of inclination angle of PV/T collectors on power, temperature, energy and exergy values were investigated. Also, effects of cellular shading are tested and discussed. PV/T was compared with the conventional PV/T collector by adding phase change material (PCM) for one of the collectors. In addition, the effect of different shading conditions (small, medium and large circle) on the power and hot water output of the PV/T collector at optimum slope angle were investigated. It is found that 7 ºC temperature differences are occurred in the hot water outlet between the PV/T collector and the PV/T-PCM collector. The highest energy efficiencies of PV/T-PCM collectors are obtained as 73.26%, 84.70% and 68.96% for slope angle 25º, 30º and 35º, respectively. The highest exergy efficiencies of shaded collectors are obtained as 11.92% for PV/T and 23.38% for PV/T-PCM.

Keywords: Photovoltaic/Thermal, Phase Change Material, Angle, Energy, Exergy, Shading

Şebekeden Bağımsız Ev Tipi Uygulamaları için PCM Destekli PV/T Kollektörlerinin Deneysel Analizi

Öz

Enerji depolamalı fotovoltaik termal kollektörlerde (PV/T) güneş enerjisinin verimini incelemek için deneysel bir çalışma yapılmıştır. Hem elektrik enerjisi hem de sıcak su üretmek için bir fotovoltaik termal kollektör imal edilmiştir. PV/T kollektörlerinin eğim açısının; güç, sıcaklık, enerji ve ekserji değerlerine etkileri ile hücresel gölgelendirmenin etkileri araştırılmıştır. PV/T kollektörlerden birinin içine faz değişim malzemesi (PCM) eklenerek PV/T kollektörüyle karşılaştırılarak farklı gölgeleme koşullarının (küçük, orta ve büyük daire) PV/T kollektörünün optimum eğim açısındaki gücü ve sıcak su çıkışı üzerindeki etkisi araştırılmıştır. PV/T kollektörü ile PV/T-PCM kollektörü arasındaki sıcak su çıkışında 7 ºC sıcaklık farkı oluştuğu bulunmuştur. PV/T-PCM kollektörünün en yüksek enerji verimleri sırasıyla 25º, 30º ve 35º eğim açısı için %73,26, %84,70 ve %68,96 olarak elde edilmiştir. Gölgeli kollektörlerin en yüksek ekserji verimleri ise PV/T kollektör için % 11,92 ve PV/T-PCM kollektörü için ise %23,38 olarak bulunmuştur.

Anahtar Kelimeler: Fotovoltaik/Termal, Faz Değiştiren Malzeme, Açı, Enerji, Ekserji, Gölgelenme

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1. Introduction

The photovoltaic panels are energy conversion systems that produce electricity by absorbing solar irradiation as well known. The waste heat is produced from the back side of the PV. So as to reduce the electrical losses in the PV systems, the cooling of the PV systems has been studied. The PV/T systems have been developed and fluids are passed through the bottom of the panel in order to distribute the heat from the PV panel. Generally, air or water is preferred as a fluid. In this way, excessive heat flow on the PV panel is stored and made available as thermal energy.

In many works, the thermal and electrical performance of air/water based PV/T panel combined with PCMs or without PCMs has been assumed. In this context, Hussain et al. (Hussain et al., 2015) experimentally studied of PV/T collector with and without hexagonal honeycomb. They obtained that the thermal efficiency of systems at the mass flow rate of 0.11 kg/s. Also, the electrical efficiency of the PV panel is developed by 0.1% during the range of the mass flow rate. Browne et al. (Browne et al., 2016) investigated the PV/T-PCM system that in outdoor conditions, generates electricity, stores heat and preheating water. The system performance was compared to different cases. They were indicated that the temperature achieved by the water was about 5.5 ºC higher when compared to a PV/T system without PCM. Fayaz et al. (Fayaz et al., 2019a) examined the performances of PV/T-PCM collectors both numerically and experimentally. They found that the electrical efficiency of the PV/T collector was 12.4% for the numerical and 12.28% for the experimental. The electrical efficiency of PV/T-PCM collector was 12.59% for numerical and 12.75% for experimental. Fayaz et al. (Fayaz et al., 2019b) tested the electrical performance of PV/T collector systems by using PCM numerically and experimentally. In the results obtained, the electrical efficiency values of the systems are 13.56% for PV panel, 13.74% for PV/T collector and 13,87% for PV/T-PCM. Hossain et al. (Hossain et al., 2019) carried out thermodynamic and economic analysis of the system using lauric acid as PCM in the PV/T collector. The highest energy and exergy efficiency values for the PV system are 9.88% and 7.09%, for PV/T-PCM systems these values are 11.08% and 12.19%, respectively. Qiu et al. (Qiu et al., 2016)examined a PV/T system with PCM as the working fluid. The results shown that the microencapsulated PCM slurry based PV/T system was superior to typical air based and water based PV/T systems. Su et al. (Su et al., 2017) presented the electrical performances of PV/T integrated with PCMs as upper and lower channel. The results showed that upper PCM mode in the PV/T collector can remarkably improve the performances of PV/T collector. Solanki et al (Solanki et al., 2009) made a comparison between theoretical and experimental results for efficiencies of PV/T collectors. They conducted his experiments in different air mass flow rate. As a result, the thermal efficiency increased with flowrate.

Agrawal and Tiwari (Agrawal and Tiwari, 2011) numerically worked on the energy and exergy analysis of micro-channel (MC) and single-channel (SC) photovoltaic thermal (PV/T) module. They observed that annual thermal and exergy gains have been increased with MCPVT module. Tiwari and Sodha (Tiwari and Sodha, 2006) investigated a thermal model for a photovoltaic/thermal water collector and informed a daily thermal efficiency of about 58%. Fudholi et al. (Fudholi et al., 2018) have theoretically and experimentally studied the thermodynamic analyses of PV/T collector with ∇-groove. They also stated that mass flow rate had a significant effect on energy efficiency, while it had a minimal effect on exergy efficiency. Zhao et al. (Zhao et al., 2019) tested their performance by adding PCM to PV panels. It contributed positively to the decrease of PV panel surface temperature and increase of output power of PCMs. Hasan et al.(Hasan et al., 2017)conducted an experimental study and used the MATLAB Simulink Toolbox for the annual energy efficiency of a hot-climate PV-PCM system. The use of PV-PCM was improved and the annual electrical energy efficiency of PV was increased by 5.9 percent in hot climate situations. An experimental study using PCMs was proposed by Radziemska and Kucharek (Klugmann-Radziemska and Wcisło-Kucharek, 2017), and the best results were obtained from the PV/PCM configuration of a steel tank PCM1 (42-44 paraffin) filled PV module. Khanna et al. (Khanna et al., 2018) analyzed the impact of the operating conditions on the optimum depth of the PCM container. The results showed that PCM thickness can be used as a control parameter for energy storage.

Rajput et al. (Rajput et al., 2016) experimentally investigated the formation of hot spots in opaque and semitransparent PV panels. In both PV panels, they indicated that the hot spot temperature decreased as hot spots increased. The efficiencies of PV panels in one and two hot spot formations were 10.41% and 10.41% for opaque panels and 10.62% and 10.54% for semitransparent panels. Dhimish et al. (Dhimish et al., 2018b) investigated the PV output power and found that the partial shading on the panel causes loss of power and increases the surface temperature of the panel. In both of the proposed techniques, the output power of the PV panel increased while the surface temperature decreased. Before and after the activation of the proposed hot spot mitigation process, Dhimish et al. (Dhimish et al., 2018a) analyzed the output power efficiency of PV panels. Bayrak et al. (Bayrak et al., 2017b) investigated the effect of partial (cellular, horizontal and vertical) shading types on energy and exergy efficiencies for PV panels. According to the data obtained, the highest negative effect on the system performance occurred in horizontal shading. The effects of shading the different sizes on PV panels were studied by Dolara et al. (Dolara et al., 2013). They suggested that as each shading rate was raised, the maximum power point decreased. In terms of their performances under partial shading of PV panels, Silvestre et al. (Silvestre, S., Chouder, 2008) compared the simulation and experimental results. They found that, due to the complete shadow of a single solar cell, the power loss of the PV module was around 30 percent.The efficiency of the photovoltaic thermal device cooled with PCM and nanofluid was investigated experimentally by Sarafraz et al.(Sarafraz et al., 2019). They also found that a photovoltaic (PV) panel can be generated between 1:30 pm and 3:30 pm at 0.2wt percent, ~ 45 percent of electricity and 44 percent of thermal power.

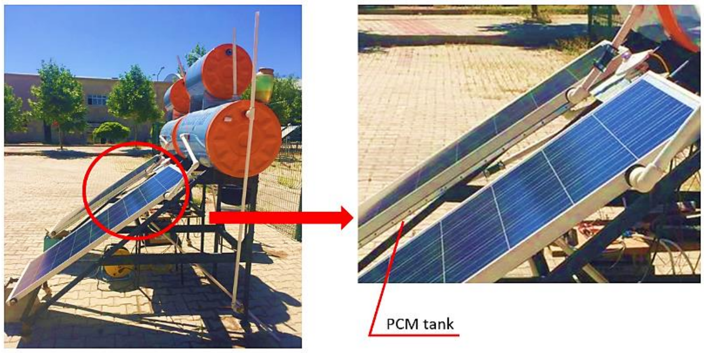
Esfe et al. (Hemmat Esfe et al., 2020) made a literature review of fluid and nanofluid applications of photovoltaic thermal systems. It was stated that the electrical efficiency of PV-PCM and PV/T nanofluid systems was increased by 15-23% and 20%-37%, respectively. Elsheniti et al. (Elsheniti et al., 2020) analyzed the temperature distribution of PV-PCM systems with CFD and a new approach "1D Enhanced Conduction Model (ECM)". In addition, electrical efficiencies of PV systems with and without PCM at different slope angles of each season in Alexandria, Egypt were obtained. Kazemian et al. (Kazemian et al., 2019) performed a numerical analysis of an integrated photovoltaic thermal system with phase change material. It was observed that the melting temperature of PCM increased from 40 ºC to 65 ºC, the surface temperature of the PV panel increased and the output power decreased. In addition, they stated that the increase in thermal conductivity of PCM increased both the electrical and thermal energy efficiency of the PV/T-PCM system. Al-Waeli et al. (Al-Waeli et al., 2020) aimed to improve the power generation performance of PV/T based on three cooling models using nanofluid, SiC-water and nano-PCM. They stated that with the correct estimates they obtained, errors in other studies can be reduced. Gan and Xiang (Gan and Xiang, 2020) experimentally investigated the effect of PCM storage thickness and fin effect on temperature and output power in PV/T systems. PV/T system 20, 30 and 50 mm thickness PCM storage was integrated and the best results were obtained from the 30 mm thick PV/T-PCM system. It has also been observed that when the fins is integrated into the 30 mm thickness PV/T-PCM system, it has a better cooling than the without fins system. Kayabaşı and Kaya (Kayabaşı and Kaya, 2019) have succeeded in reducing the system surface temperature by using thermoelectric modules and phase change materials from the waste heat of photovoltaic panels. Gani et al. (Gani et al., 2020) investigated the tracking of photovoltaic panels' maximum power points under varying load and solar radiation with neural fuzzy controllers. The proposed follow-up structure stated that in both cases, the photovoltaic system is better adapted to the changes in the maximum power operating point than the incremental conductivity method.

The main purpose of this experimental study is to use the waste heat generated on the PV surface as thermal energy and to benefit more from the PV efficiency. Furthermore, in addition to generating electricity from photovoltaic systems that are advancing rapidly among renewable energy systems, cooling of these systems with cheap methods gives hope to use in industrial scale projects. For this reason, $CaCl_2.6H_2O$, which is cost effective, has high thermal conductivity and is easy to obtain, has been chosen in the system. In addition, the electrical and thermodynamic analysis of the PV/T collectors under different partial shading has been examined and provided a detailed analysis.

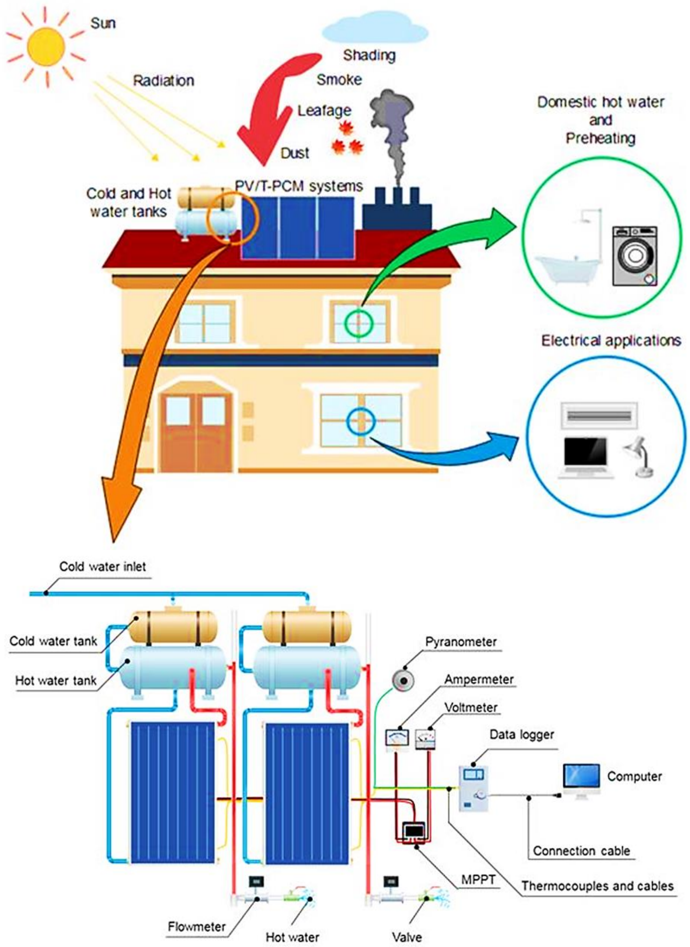
2. Material and Method

2.1. Experimental Setup

The experiments were carried out in Firat University, Turkey. Experiments were carried out on days when the weather was not cloudy for July, 2017. PV/T collector was designed by installing copper piping on the back of the panels in order to use the waste heat in the PV panels as thermal energy. The PV/T-PCM collector is designed by filling the empty parts of the PV/T collector with Calcium Chloride Hexahydrate (PCM). Since the circulation pump is not used in newly designed systems, the power obtained from the system is equal to the net power ($P=P_{net}$). PV and PV/T collectors were tested and compared at different inclination angles (φ=25º, 30º and 35º). The electrical and thermal performances of PV/T collectors were investigated by applying artificial cellular shading of different sizes (small, medium and large) on PV/T collectors with and without PCM at optimum slope angle. From the experiments, power, radiation, hot water, energy and exergy analysis are obtained. All tests were taken between 9 a.m. and 6 p.m. The images and schematic diagram of the experimental setups are shown in Fig. 1 (a-b). Fig. 2 exhibits the artificial cellular shading in the PV/T collectors. 3 different shading is used. In the first shading, a circular non-transparent material with a radius of 40 mm, a circular object with a 78 mm radius so that the second shading is tangent to the cell edges, and a 97.5 mm radius artificial shading was used in the third shading over the cell edges. According to the area ratio, the first shading was found to be Ar_1 = 0.20, the second shading Ar_2 = 0.80 and the third shading Ar_3 = 1.20.



(a)



(b)

Figure 1. (a) The side view (b) schematic of PV/T systems

All temperature values in experimental measurements were measured with T-type thermocouple (OMEGA). The sensitivity of thermocouples is ± 0.5% between -200 °C and +300 °C. KIPP & ZONEN-CMP3 model was used to measure solar radiation, and CEM-DT-619 model anemometer was used to measure wind speed. The sensitivities of these devices are s ± 0.05 between -40 °C and +40 °C, ± 0.1 between +40 °C and + 80 °C, ± 0.2 m / s, respectively. The multimeter is used to measure current and voltage values and the accuracy of this device is ±0.1 for current and voltage values. The KEITHLEY brand 2701 model 40 channel datalogger was used to transfer all values to the computer. The $CaCl_2.6H_2O$ from Sigma-Aldrich (98% purity) was used as

PCM for the PV panel to storage heating for water. The specifications of this PCM are measured and given in Table 1. In the experiments, two polycrystalline PV panels were used and each panel has 150W power. The properties of the PV panels are also shown in Table 2. The DSC analysis of PCM ($CaCl_2.6H_2O$) is given Fig. 3.

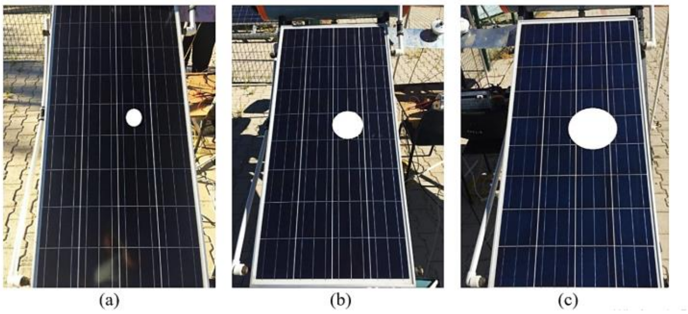


Figure 2. Cellular shading in PV/T collectors with and without PCM (a) Ar_1=0.20, (b) Ar_2=0.80 and (c) Ar_3=1.20

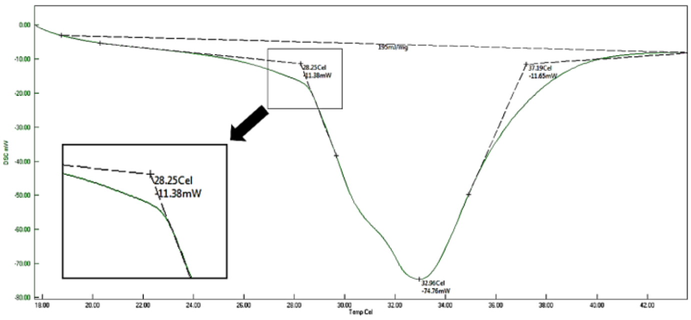


Figure 3. DSC analysis of PCM used in experiments

Table 1. Physical properties of PCM (Rezvanpour et al., 2020)

Property	**Catalog values**	**Measured values**
Melting point (°C)	29	28.25
Latent heat capacity (kJ/kg)	195	210.12
Heat cond. coeff. (solid) (W/mK)	1.088	1.09
Heat cond. coeff. (liquid) (W/mK)	0.536	0.54

Table 2. Technical properties of the PV panel

Parameters	**Values**
Dimensions of the PV module	1480x680x35 mm
Dimensions of a solar cell	156x156
Thickness of the glass cover	3.2 mm
Thickness of the EVA	0.5 mm
Thickness of the solar cells	0.3 mm
Thickness of the Tedlar	0.35 mm
Maximum Power (STC) (P_m)	150 W
Open-Circuit Voltage (V_{oc})	22.36 V
Optimum Operating Voltage (V_m)	18.79 V
Short-Circuit Current (I_{sc})	8.52 A
Operating Current (I_m)	7.98 A
Operating Temperature (°C)	-40 to 85

2.1.1. Energy and Exergy Analysis of PV/T

The energy efficiency of the PVs is defined as the ratio of the input energy of the system to the output. Electrical efficiency of PV/T was calculated with equation is reported by Tiwari et al. (Bayrak et al., 2020; Tiwari et al., 2009).

$$\eta_{elec.PV} = \frac{I_{\max} V_{\max}}{I_s A} \tag{1}$$

The energy of PV/T systems are related to two main components, electricity and heat. Although electricity is produced due to photovoltaic effect, the cells are heated by solar radiation. The thermal energy on the top surface of the photovoltaic panel is not useful energy. The energy output from the photovoltaic system can be defined as follows (Bayrak et al., 2017a, 2017b; Hepbasli, 2008; Petela, 2008)

$$\dot{E}n_o = \dot{E}n_e + \dot{E}n_t = V_{oc} I_{sc} + Q \tag{2}$$

Exergy output from the photovoltaic system is expressed as follows

$$\dot{E}x_o = \dot{E}x_e + \dot{E}x_t + \dot{E}x_d = \dot{E}x_e + I' \tag{3}$$

here I' is;

$$I' = \dot{E}x_t + \dot{E}x_d \tag{4}$$

This equation contains both internal contains losses. The exergy and heat loss are:

$$\dot{E}x_e = \dot{E}n_e - I' \tag{5}$$

$$\dot{E}x_e = V_{oc} I_{sc} - \left(V_{oc} I_{sc} - V_m I_m\right) \tag{6}$$

In Eq. (5), the first expression ($V_{oc} I_{sc}$) is the electrical energy and the second expression $\left(V_{oc} I_{sc} - V_m I_m\right)$ represents the exergy deterioration resulting from irreversibility. These two differences express the electrical exergy as follows

$$\dot{E}x_e = V_m I_m \tag{7}$$

The thermal exergy ($\dot{E}x_t$) of the system consists of the loss of heat from the upper surface of the cells and is expressed in thermodynamics as follows (Bayrak et al., 2019).

$$\dot{E}x_t = \left(1 - \frac{T_a}{T_c}\right) \dot{Q} \tag{8}$$

where

$$\dot{Q} = h_{ca} A \left(T_c - T_a\right) \tag{9}$$

$$h_{ca} = 5.7 + 3.8v \tag{10}$$

The electrical and thermal exergy of a PV/T systems is:

$$\dot{E}x_o = V_m I_m + \left(1 - \frac{T_c}{T_a}\right) h_{ca} A (T_c - T_a) \quad (11)$$

Input exergy of a PV system is (Hepbasli, 2008; Selimefendigil et al., 2018)

$$\dot{E}x_i = \left(1 - \frac{T_a}{T_s}\right) I_s A \quad (12)$$

where T_s is value as 5777 K.

Exergy efficiency of the system;

$$\eta_{II} = \frac{\dot{E}x_o}{\dot{E}x_i} \quad (13)$$

can be calculated.

2.1.2. Uncertainty analysis

In order to show the precision of the data in experimental tests, a study of the uncertainty of the instruments used should be carried out. In experiments, measured values (R) and effective parameters of n independent parameters (x_1, x_2, ……… … x_n) are defined. Error ratio for each variable and calculated are found as W_1, W_2, ………W_n.(Bakır, 2017; Esen, 2008; Holman, J.P., 1994).

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} W_1\right)^2 + \left(\frac{\partial R}{\partial x_2} W_2\right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} W_n\right)^2\right]^{1/2} \quad (16)$$

3. Results and Discussion

In this experimental study inclination angle on a novel designed PV/T collector with and without phase change material (PCM). In addition, the output power, hot water output and efficiency values in different shading conditions were analyzed in PV/T collectors at optimum slope angle.

Optimum inclination angles and load resistance of the PV panels were determined before starting the experiments. Table 3 shows the current-voltage values of PV panels under the same environmental conditions. The reached highest power is: the panel at 30 degrees with 82.79 W at 1034 W/m^2 solar radiation at 12:00.

Table 3. Current-voltage values of PV panels at different tilt angles

Time	Inclination angles						Radiation (W/m^2)
	25°		30°		35°		
	I_m	V_m	I_m	V_m	I_m	V_m	
09:00	5.55	12.06	5.58	12.34	5.56	12.01	762.1516
09:30	5.63	12.39	5.66	12.55	5.63	12.59	844.2997
10:00	5.75	12.84	5.77	13.01	5.76	12.92	911.5988
10:30	5.89	12.9	5.93	13.46	5.9	13.04	983.279
11:00	6.02	13.05	6.04	13.53	6.02	13.24	1016.2644
11:30	6.04	13.07	6.05	13.6	6.03	13.26	1027.9872
12:00	6.05	13.08	6.07	13.64	6.04	13.29	1034.8557
12:30	6.01	12.86	6.03	13.61	6.02	13.07	1029.8015
13:00	5.95	12.7	5.97	13.43	5.97	12.96	1017.6934
13:30	5.78	12.61	5.8	13.17	5.8	12.87	999.4123
14:00	5.68	12.46	5.74	12.95	5.69	12.57	941.3265
14:30	5.6	12.42	5.66	12.65	5.67	12.52	880.1496
15:00	5.51	12.39	5.59	12.54	5.57	12.33	787.8873

The maximum power point changes with the power of the PVs and the internal resistance of the system. Fig.4 illustrates the variation of resistance with power at different solar radiation values. The PV/T system was measured as 81.25 W under 985 W/m^2 radiation and 65.61 W in 680 W/m^2 radiation when the system had a 30° slope angle. In both solar radiation value, the load resistance of the system is measured as 2.5 ohms. In Fig. 4 shows the power values of a panel.

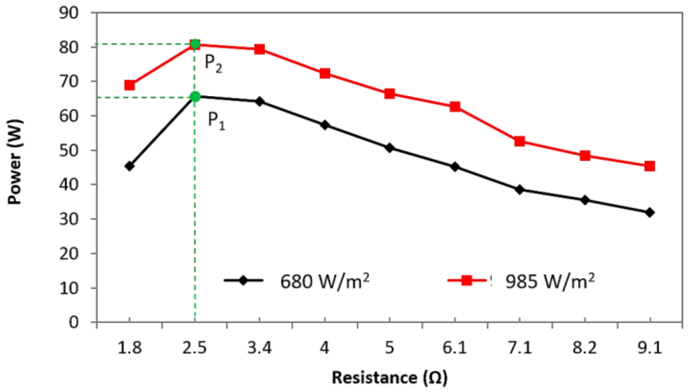


Figure 4. Determination of maximum power point at different resistance values

The experiments were taken once for every half an hour between 09:00 and 18:00 and the results were compared with each other. Power exchange of the PV/T with and without PCM depending on the radiation of the collector with a slope angle of 25° is shown in Fig 5 (a). Using of a PCM enhances the electrical power. The highest value of power was obtained at 11:30 in the collector with PCM. It is seen that these maximum values are obtained as 79.77 W and 77.17 W the PCM systems, respectively. As seen from the figure that for all cases higher power is formed for collector with the PCM. The obtained power goes 2 Watt around 18:00. Even at 18:00 higher power is formed for collector with the PCM. The power exchange for PV/T collector PCM depending on the solar radiation of the collector with a slope angle of 30° is indicated Fig. 5 (b). In this case the highest value of power is obtained around 12:00 and with 83.65 W. In PV/T without PCM the power rating is lower and the value is measured as about 82.01 W while the radiation value was measured as 1080 W/m^2. It means that addition of the PCM is helped to cool PV panel. Thus, its power is increased with the using of the PCM. The power change of 35° inclined PV/T collectors is given in Figure 5 (c). The highest value reached at 12:00 and a measured at about 80.09 W. In PV/T without PCM the power rating is lower and the value is measured as about 78.37 W.

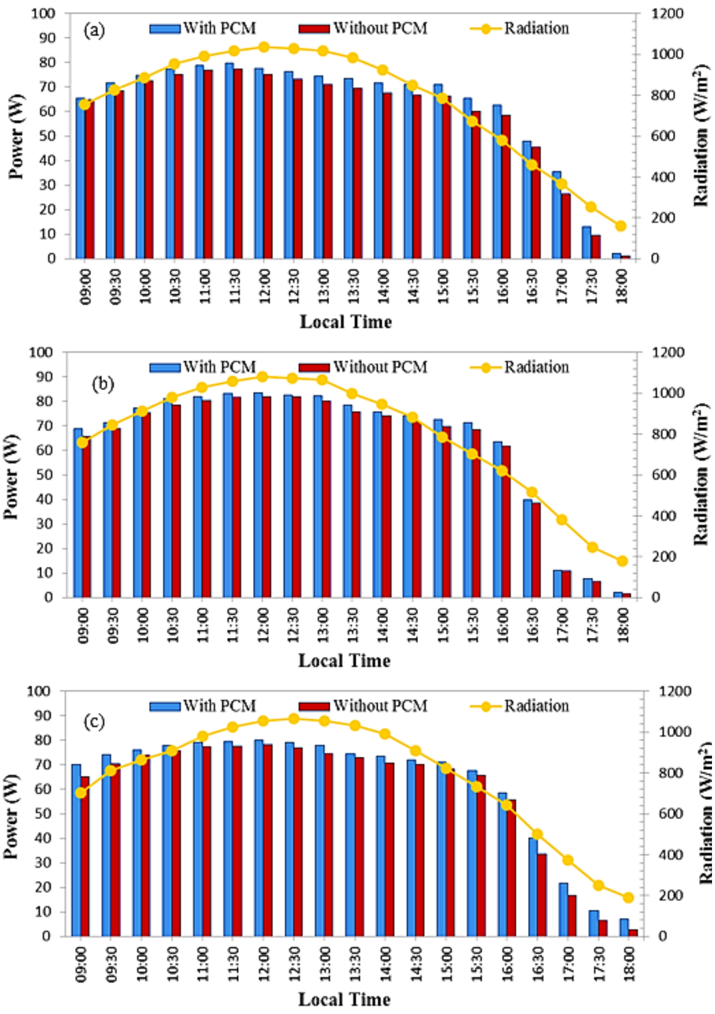


Figure 5. Power change of PV/T collectors with and without PCM depending on solar radiation during the daily (a) φ=25°, (b) φ=30°, (c) φ=35°

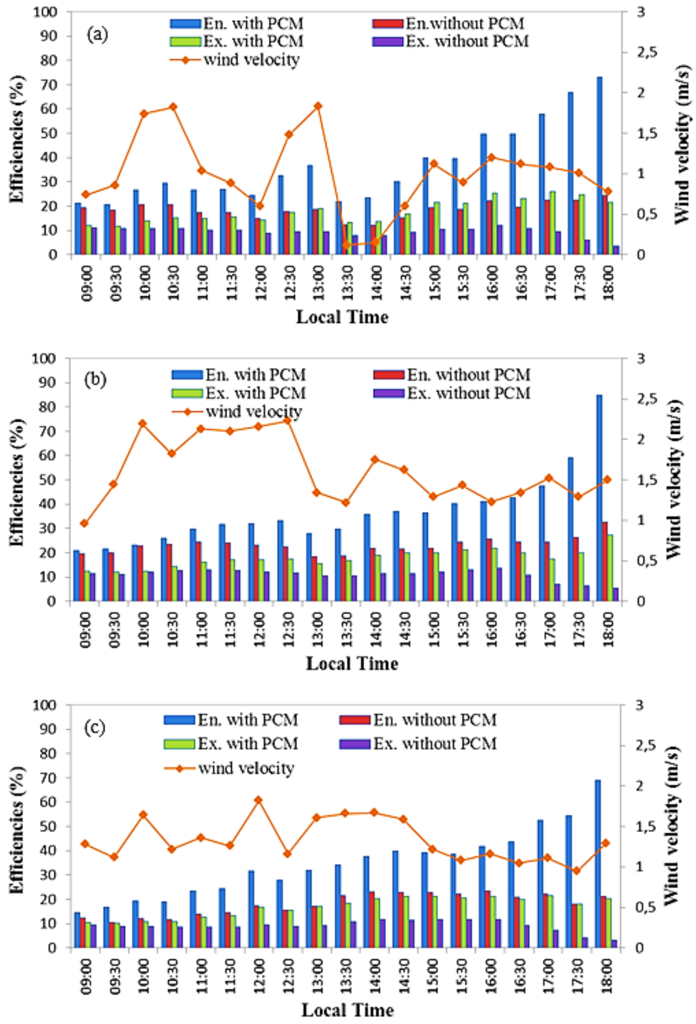


Figure 6. Energy and exergy efficiencies for PV/T collectors with and without PCM at (a) φ=25°, (b) φ=30°, (c) φ=35°

Figure 6 shows the variation according to time in energy and exergy efficiencies of PV/T with 25°, 30° and 35° inclination angles. In Figure 6 (a), the highest efficiencies of the PV/T PCM collectors were recorded as 73.26% and 24.53% at 18:00, 25.40% and 12.05% at 16:00. Even though the power values decrease in the evening hours, the reason for the high efficiency values can be explained as the positive effect of beneficial heat on the system. Figures 6 (a-c) shows the increase in the efficiency of the collectors at the 25° inclination angle at 13:30 when the solar radiation is highest. This is caused by an increase in solar radiation and an increasing of the temperature of the PV surface. The minimum wind speed in Figure 6 (a) adversely affected the efficiency values. In order to have high efficiency values, panel surface temperature should be low and wind speed should be high. Increasing or increasing the output power by cooling the photovoltaic panels is related to these terms. In Figure 6 (b), the highest efficiencies are 84.7% and 27.16% for PVT-PCM collector, 32.51% and 13.10% for PV/T collector, respectively. In Figure 6 (c), the highest energy and exergy efficiency values are 68.96% and 21.58% for PVT-PCM collector, 23.57% and 11.89% for PV/T collector, respectively.

Table 4 shows the hot water values of PV/T collectors with 25°, 30°and 35° angle of inclination. The temperature of the mains water is about 26 °C within 3 days of the experiments. The highest leaving water temperature obtained for generally taken from 25° inclined construction. The difference between the hot water outlets of the PV/T collectors at different angles of inclination varied between about 0.55 °C and 1 °C. In the PV/T-PCM, the hot water output of the 25° inclined collector was higher than the others. The difference between the hot water outlets of the PV/T-PCM collectors is about 0.5 °C. Since the melting temperature of the phase-changing material is about 30 °C, the hot water outlets of the PV/T-PCM collectors are measured between 30 °C and 33 °C. The difference between the hot water outlets is about 7 °C. In general, PV/T collectors increased the mains water by 7 °C and 15 °C. The results for uncertainty are listed in Table 5. According to the results of this analysis, the uncertainty results of all parameters are less than 2%. This value can be accepted.

Table 4.Hot water outlets at PV/T systems (a) φ = 25°, (b) φ = 30°, (c) φ = 35

Time	Main water (°C)	Temperatures (°C)					
		PV/T			PV/T-PCM		
		25°	30°	35°	25°	30°	35°
09:00	26.99	33.30	36.60	**36.88**	**31.17**	30.86	29.32
09:30	26.41	**37.44**	35.99	36.81	**32.00**	31.40	29.59
10:00	26.59	**37.65**	37.41	36.92	**32.07**	32.05	29.70
10:30	26.64	**38.25**	37.30	36.75	**32.69**	31.64	29.99
11:00	26.66	**38.65**	36.74	36.68	**32.59**	31.88	30.50
11:30	26.68	**38.99**	37.92	37.48	**32.57**	32.08	30.98
12:00	26.15	**39.12**	38.79	38.21	**32.89**	32.40	31.21
12:30	26.98	**39.36**	39.09	38.70	**33.36**	32.75	31.83
13:00	26.49	**40.27**	39.78	38.66	**33.65**	32.76	32.13
13:30	26.06	**40.39**	39.92	39.40	**33.94**	33.33	32.24
14:00	26.70	**41.37**	40.55	39.60	**34.00**	33.09	32.71
14:30	26.19	40.29	40.49	**40.99**	**33.83**	33.39	33.16
15:00	26.62	**42.48**	39.73	41.15	**33.98**	33.58	33.64
15:30	26.39	**41.63**	40.11	41.34	**33.70**	33.55	33.41
16:00	26.80	40.92	40.34	**41.13**	**33.65**	33.48	33.40
16:30	26.55	**40.72**	40.12	40.48	**33.99**	33.20	33.43
17:00	26.85	40.64	40.16	**41.35**	**33.92**	33.25	33.02
17:30	26.81	40.16	39.24	**40.24**	**33.07**	32.89	33.36
18:00	26.47	38.17	39.12	**40.54**	**32.81**	32.13	33.22

Table 5. Results for Uncertainty analysis.

Description	Unit	Total uncertainty (%)
Temperatures	°C	±0.702
Velocity	m/s	±0.034
Solar Irradiance	W/m²	±0.026
Current	A	±0.83
Power	W	±1.50

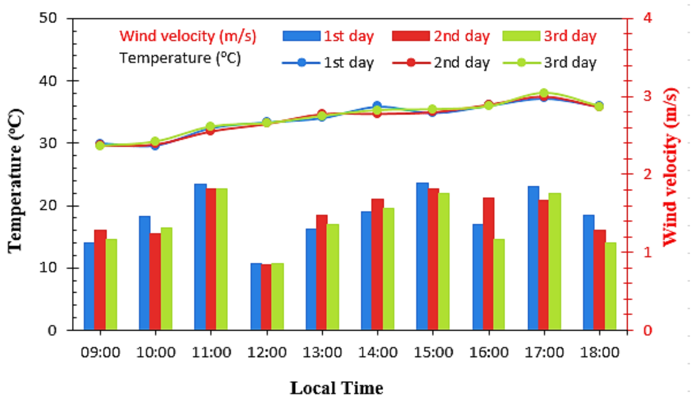


Figure 7. Environmental temperature and wind velocity values for different test days

In Table 6, hot water values of PV/T collectors in different shading conditions are given according to time. Figure 7 shows the ambient temperature and wind speed values on these test days. Ambient temperature did not change on consecutive test days. Although the wind speed varies between 1-2 m/s, it could not reach the speed that will play an active role in the cooling of PV panels. The closest temperature and wind speed values of the three days were recorded as 12:00. The maximum temperature difference between the hot water output values of the shaded PV/T collectors at this measuring point is 2.72 °C for the PV/T collector and 1.16 °C for the PV/T-PCM collector. Furthermore, the solar radiation values of these days at 12:00 are 1053, 1060 and 1059 W/m², respectively. At the end of these tests, it was seen that different parameters can be tested on different days.

Table 6. Hot water outlets of PV/T collectors in different shading conditions (inlet water °C = 25 °C)

Time	Temperatures (°C)					
	1st day Ar_1=0.20		2nd day Ar_2=0.80		3rd day Ar_3=1.20	
	PV/T	PV/T-PCM	PV/T	PV/T-PCM	PV/T	PV/T-PCM
09:00	37.28	30.05	38.04	30.50	38.69	30.95
10:00	37.24	30.29	38.27	30.90	38.33	31.50
11:00	38.85	31.46	39.36	31.68	39.31	32.15
12:00	38.88	32.03	40.46	32.59	41.60	33.19
13:00	40.81	33.04	40.88	33.27	41.82	33.66
14:00	40.61	33.67	41.50	34.33	41.83	34.36
15:00	40.85	34.62	43.34	34.26	43.29	34.63
16:00	41.04	34.32	43.07	34.20	41.79	34.65
17:00	41.82	33.79	42.03	34.41	40.91	34.80
18:00	42.11	33.63	42.42	34.59	40.07	34.62

In Fig. 8, the PV/T collector is shaded to be small, medium and large on a cell in the second row from the right. The purpose of this shading is to investigate the electrical losses that may occur in any shading scenarios that may occur in PV/T collectors. In general, shading occurs in either cellular or horizontal array in PV/T systems. Sometimes diagonal (triangular) shading types are seen. Shading of different sizes on any cell selected on the PV/T collector adversely affects the output power of the PV/T collector. A small shading at the very center of the solar cell selected in Figure 8 (a) results in very small losses in the output power of the PV/T collector. In Fig. 8 (b and c), it is seen that the output power decreases considerably in a shade of the same selected solar cell diameter and size exceeding its diameter. This is due to the activation of the bypass diode connected to the PV panels in the event of shading and the failure of current to complete the electrical circuit over all solar cells. Table 7 shows the exergy values of partially shaded PV/T collectors.

4. Conclusions and Recommendations

In this study, Calcium Chloride Hexahydrate (PCM) was selected as energy storage element and used in water based PV/T collector. The thermal, electrical and thermodynamic values of PV/T and PV/T-PCM collectors were compared. In addition, different shading scenarios that may occur in the system have been studied experimentally. It is found as:

- The panel with 30° slope produces more power during the day than the panels with other angles. Also, it has been observed the hot water temperature with the inclination a tilt of 25 degrees is higher than that of the panels with the inclination of 30, 35 degrees.
- The highest panel surface temperatures during the day were measured in 25° inclined collectors. In addition, the average surface temperature was measured as the highest in these collectors.

- Different angular panels give different power according to the geographical position in which they are located. According to Elazig's geographical position, it is decided that the highest power was reached at the 30 degree of the panel.
- In the PV/T-PCM collectors, a PCM with a high melting temperature should be selected when the leaving water temperature is desired.
- Cellular shading had a negative effect on producing the electricity and had a positive effect on hot water output.

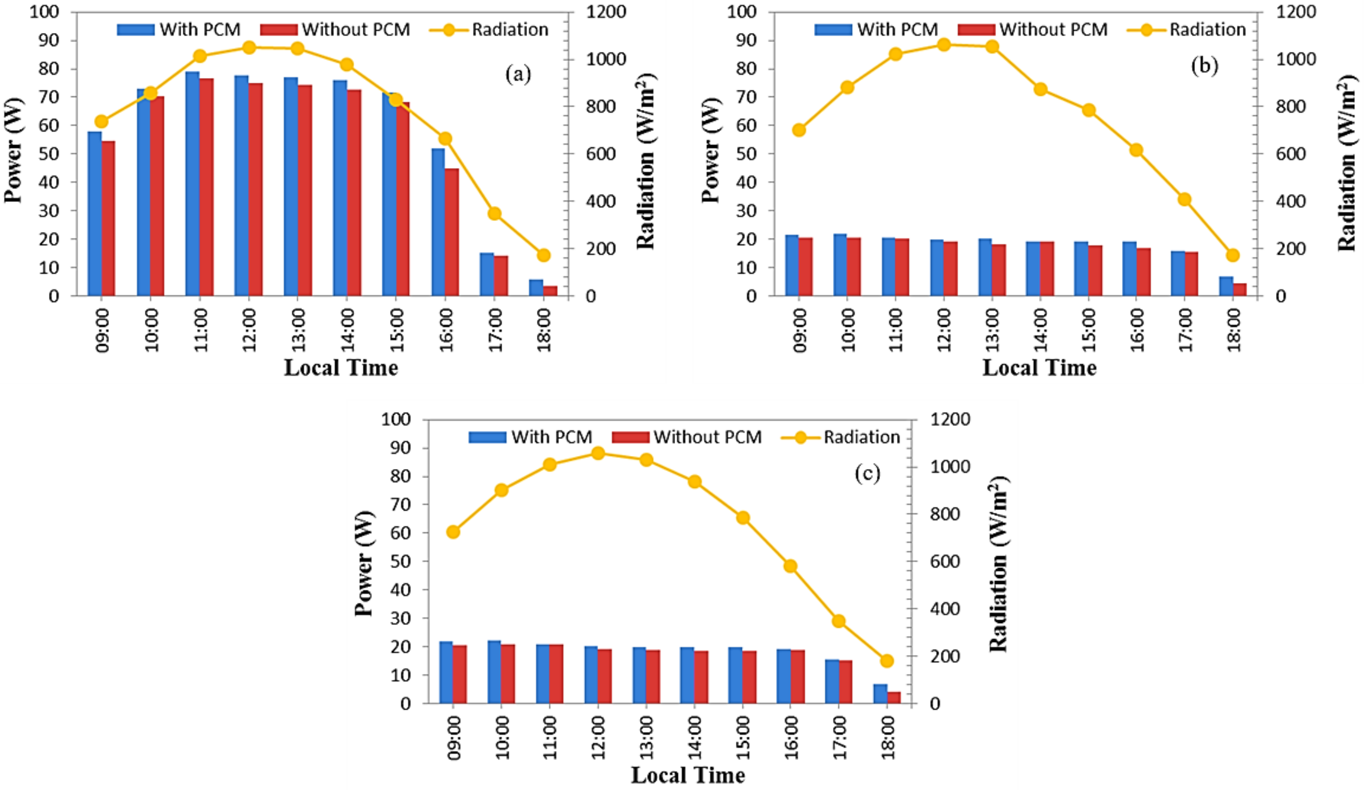


Figure 8. Output power variations of PV/T collectors at different shading rates (a) Ar_1=0.20 (b) Ar_2 =0.80 (c) Ar_3=1.20

Table 7. Electrical exergy, thermal exergy and exergy efficiency values of PV/T collectors for PCM in different shading scenarios

Local Time	$\dot{E}x_e$ (W)			$\dot{E}x_t$ (W)			η_{II}		
	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large
PV/T									
09:00	54.49	20.43	20.58	19.71	22.38	19.30	10.04	6.08	5.49
10:00	70.17	20.59	20.91	32.00	38.12	16.54	11.92	6.65	4.15
11:00	76.73	20.31	20.88	24.33	26.89	29.03	9.94	4.61	4.94
12:00	75.13	19.22	19.30	24.49	21.68	18.68	9.46	3.85	3.58
13:00	74.21	18.20	18.93	23.05	20.80	27.61	9.28	3.70	4.51
14:00	72.70	19.14	18.56	20.37	29.99	17.99	9.50	5.61	3.90
15:00	68.20	17.95	18.40	29.20	30.15	25.20	11.75	6.12	5.56
16:00	44.96	16.88	18.82	12.92	19.15	9.53	8.72	5.84	4.87
17:00	14.09	15.50	15.14	8.89	4.14	4.31	6.56	4.80	5.56
18:00	3.56	4.34	4.19	1.19	1.09	3.32	2.75	3.15	4.20
PV/T-PCM									
09:00	58.04	21.66	21.97	17.31	12.23	12.79	10.20	4.81	4.78
10:00	73.11	21.92	22.24	52.67	55.01	23.78	14.67	8.71	5.11
11:00	78.98	20.51	20.81	82.12	86.82	63.11	15.85	10.48	8.31
12:00	77.81	19.84	20.17	75.46	73.28	58.67	14.56	8.77	7.44
13:00	76.91	20.04	19.94	89.71	96.26	99.28	15.90	11.02	11.54
14:00	75.93	19.23	19.82	94.65	120.99	68.29	17.41	16.01	9.40
15:00	71.51	19.29	19.69	122.24	120.01	93.79	23.38	17.72	14.46
16:00	52.03	19.07	19.30	71.44	93.22	40.12	18.59	18.21	10.20
17:00	15.28	15.81	15.65	55.94	29.03	30.77	20.32	10.97	13.26
18:00	5.91	6.87	6.81	27.52	20.06	25.92	19.34	15.61	18.30

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Nomenclature

A	Area (m^2)
DSC	Differential scanning calorimetry
En	Energy (W)
Ex	Exergy (W)
h_{ca}	Heat transfer coefficient (W/m^2K)
I	Current (A)
I_s	Solar radiation (W/m^2)
PCM	Phase change material
PV	Photovoltaic
PV/T	Photovoltaic/Thermal
V	Voltage (V)
Q	Heat emitted to the surrounding (W)
v	Wind velocity (m/s)
W	Uncertainty in the measurement (%)
Greek letters	
η	energy efficiency (-)
η_{II}	exergy efficiency (-)
Subscripts	
a	ambient
c	cell
d	destroyed
e, elec	electrical
i	input
L	load
max	maximum
oc	open circuit
o	Output
s	sun
sc	short circuit
t	thermal

References

Agrawal, S., Tiwari, G.N., 2011. Energy and exergy analysis of hybrid micro-channel photovoltaic thermal module. Solar Energy 85, 356–370. https://doi.org/10.1016/j.solener.2010.11.013

Al-Waeli, A.H.A., Kazem, H.A., Yousif, J.H., Chaichan, M.T., Sopian, K., 2020. Mathematical and neural network modeling for predicting and analyzing of nanofluid-nano PCM photovoltaic thermal systems performance. Renewable Energy 145, 963–980. https://doi.org/10.1016/j.renene.2019.06.099

Bakır, E., 2017. Enerji depolamalı yeni nesil fotovoltaik/termal kolektörlerin ısıl performanslarının incelenmesi. Master's Thesis, Fırat University.

Bayrak, F., Abu-Hamdeh, N., Alnefaie, K.A., Öztop, H.F., 2017a. A review on exergy analysis of solar electricity production. Renewable and Sustainable Energy Reviews 74, 755–770. https://doi.org/10.1016/j.rser.2017.03.012

Bayrak, F., Ertürk, G., Oztop, H.F., 2017b. Effects of partial shading on energy and exergy efficiencies for photovoltaic panels. Journal of Cleaner Production 164, 58–69. https://doi.org/10.1016/j.jclepro.2017.06.108

Bayrak, F., Oztop, H.F., Selimefendigil, F., 2020. Experimental study for the application of different cooling techniques in photovoltaic (PV) panels. Energy Conversion and Management 212, 112789. https://doi.org/10.1016/j.enconman.2020.112789

Bayrak, F., Oztop, H.F., Selimefendigil, F., 2019. Effects of different fin parameters on temperature and efficiency for cooling of photovoltaic panels under natural convection. Solar Energy 188, 484–494. https://doi.org/10.1016/j.solener.2019.06.036

Browne, M.C., Norton, B., McCormack, S.J., 2016. Heat retention of a photovoltaic/thermal collector with PCM. Solar Energy 133, 533–548. https://doi.org/10.1016/j.solener.2016.04.024

Dhimish, M., Holmes, V., Mather, P., Sibley, M., 2018a. Novel hot spot mitigation technique to enhance photovoltaic solar panels output power performance. Solar Energy Materials and Solar Cells 179, 72–79. https://doi.org/10.1016/j.solmat.2018.02.019

Dhimish, M., Holmes, V., Mehrdadi, B., Dales, M., Mather, P., 2018b. PV output power enhancement using two mitigation techniques for hot spots and partially shaded solar cells. Electric Power Systems Research 158, 15–25. https://doi.org/10.1016/j.epsr.2018.01.002

Dolara, A., Lazaroiu, G.C., Leva, S., Manzolini, G., 2013. Experimental investigation of partial shading scenarios on PV (photovoltaic) modules. Energy 55, 466–475. https://doi.org/10.1016/j.energy.2013.04.009

Elsheniti, M.B., Hemedah, M.A., Sorour, M.M., El-Maghlany, W.M., 2020. Novel enhanced conduction model for predicting performance of a PV panel cooled by PCM. Energy Conversion and Management 205, 112456. https://doi.org/10.1016/j.enconman.2019.112456

Esen, H., 2008. Experimental energy and exergy analysis of a double-flow solar air heater having different obstacles on absorber plates. Building and Environment 43, 1046–1054. https://doi.org/10.1016/j.buildenv.2007.02.016

Fayaz, H., Rahim, N.A., Hasanuzzaman, M., Nasrin, R., Rivai, A., 2019a. Numerical and experimental investigation of the effect of operating conditions on performance of PVT and PVT-PCM. Renewable Energy 143, 827–841. https://doi.org/10.1016/j.renene.2019.05.041

Fayaz, H., Rahim, N.A., Hasanuzzaman, M., Rivai, A., Nasrin, R., 2019b. Numerical and outdoor real time experimental investigation of performance of PCM based PVT system. Solar Energy 179, 135–150. https://doi.org/10.1016/j.solener.2018.12.057

Fudholi, A., Zohri, M., Jin, G.L., Ibrahim, A., Yen, C.H., Othman, M.Y., Ruslan, M.H., Sopian, K., 2018. Energy and exergy analyses of photovoltaic thermal collector with □-groove. Solar Energy 159, 742–750. https://doi.org/10.1016/j.solener.2017.11.056

Gan, G., Xiang, Y., 2020. Experimental investigation of a photovoltaic thermal collector with energy storage for power generation, building heating and natural ventilation.

Renewable Energy 150, 12–22. https://doi.org/10.1016/j.renene.2019.12.112

Gani, A., Açıkgöz, H., Şekkeli, M., 2020. Fotovoltaik Sistemlerde Değişken Yük ve Güneş Işınımı Altında Sinirsel-Bulanık Denetleyici ile Maksimum Güç Noktası Takibi Maximum Power Point Tracking with Neuro-Fuzzy Controller Under Variable Load and Solar Irradiance in Photovoltaic Systems 734–745. https://doi.org/10.31590/ejosat.748384

Hasan, A., Sarwar, J., Alnoman, H., Abdelbaqi, S., 2017. Yearly energy performance of a photovoltaic-phase change material (PV-PCM) system in hot climate. Solar Energy 146, 417–429. https://doi.org/10.1016/j.solener.2017.01.070

Hemmat Esfe, M., Kamyab, M.H., Valadkhani, M., 2020. Application of nanofluids and fluids in photovoltaic thermal system: An updated review. Solar Energy 199, 796–818. https://doi.org/10.1016/j.solener.2020.01.015

Hepbasli, A., 2008. A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renewable and Sustainable Energy Reviews 12, 593–661. https://doi.org/10.1016/j.rser.2006.10.001

Holman, J.P., 1994. Experimental Methods for Engineers, sixth ed. ed. McGraw-Hill.

Hossain, M.S., Pandey, A.K., Selvaraj, J., Abd, N., Islam, M.M., Tyagi, V. V, 2019. Two side serpentine fl ow based photovoltaic-thermal-phase change materials (PVT-PCM) system : Energy , exergy and economic analysis. Renewable Energy 136, 1320–1336. https://doi.org/10.1016/j.renene.2018.10.097

Hussain, F., Othman, M.Y.H., Yatim, B., Ruslan, H., Sopian, K., Anuar, Z., Khairuddin, S., 2015. An improved design of photovoltaic/thermal solar collector. Solar Energy 122, 885–891. https://doi.org/10.1016/j.solener.2015.10.008

Kayabaşı, R., Kaya, M., 2019. Fotovoltaik Modüllerin Atık Isılarından Termoelektrik Jeneratör İle Elektrik Üretimi. European Journal of Science and Technology 310–324. https://doi.org/10.31590/ejosat.562859

Kazemian, A., Salari, A., Hakkaki-Fard, A., Ma, T., 2019. Numerical investigation and parametric analysis of a photovoltaic thermal system integrated with phase change material. Applied Energy 238, 734–746. https://doi.org/10.1016/j.apenergy.2019.01.103

Khanna, S., Reddy, K.S., Mallick, T.K., 2018. Optimization of solar photovoltaic system integrated with phase change material. Solar Energy 163, 591–599. https://doi.org/10.1016/j.solener.2018.01.002

Klugmann-Radziemska, E., Wcisło-Kucharek, P., 2017. Photovoltaic module temperature stabilization with the use of phase change materials. Solar Energy 150, 538–545. https://doi.org/10.1016/j.solener.2017.05.016

Petela, R., 2008. An approach to the exergy analysis of photosynthesis. Solar Energy 82, 311–328. https://doi.org/10.1016/j.solener.2007.09.002

Qiu, Z., Ma, X., Zhao, X., Li, P., Ali, S., 2016. Experimental investigation of the energy performance of a novel Micro-encapsulated Phase Change Material (MPCM) slurry based PV/T system. Applied Energy 165, 260–271. https://doi.org/10.1016/j.apenergy.2015.11.053

Rajput, P., Tiwari, G.N., Sastry, O.S., 2016. Thermal modelling and experimental validation of hot spot in crystalline silicon photovoltaic modules for real outdoor condition. Solar Energy 139, 569–580. https://doi.org/10.1016/j.solener.2016.10.016

Rezvanpour, M., Borooghani, D., Torabi, F., Pazoki, M., 2020. Using CaCl2·6H2O as a phase change material for thermo-regulation and enhancing photovoltaic panels' conversion efficiency: Experimental study and TRNSYS validation. Renewable Energy 146, 1907–1921. https://doi.org/10.1016/j.renene.2019.07.075

Sarafraz, M.M., Safaei, M.R., Leon, A.S., Tlili, I., Alkanhal, T.A., Tian, Z., Goodarzi, M., Arjomandi, M., 2019. Experimental investigation on thermal performance of a PV/T-PCM (photovoltaic/thermal) system cooling with a PCM and nanofluid. Energies 12, 1–16. https://doi.org/10.3390/en12132572

Selimefendigil, F., Bayrak, F., Oztop, H.F., 2018. Experimental analysis and dynamic modeling of a photovoltaic module with porous fins. Renewable Energy 125, 193–205. https://doi.org/10.1016/J.RENENE.2018.02.002

Silvestre, S., Chouder, A., 2008. Effects of shadowing on photovoltaic module performance. Progress in Photovoltais: Research and Applications 16, 141–149. https://doi.org/10.1002/pip

Solanki, S.C., Dubey, S., Tiwari, A., 2009. Indoor simulation and testing of photovoltaic thermal (PV/T) air collectors. Applied Energy 86, 2421–2428. https://doi.org/10.1016/j.apenergy.2009.03.013

Su, D., Jia, Y., Alva, G., Liu, L., Fang, G., 2017. Comparative analyses on dynamic performances of photovoltaic–thermal solar collectors integrated with phase change materials. Energy Conversion and Management 131, 79–89. https://doi.org/10.1016/j.enconman.2016.11.002

Tiwari, A., Dubey, S., Sandhu, G.S., Sodha, M.S., Anwar, S.I., 2009. Exergy analysis of integrated photovoltaic thermal solar water heater under constant flow rate and constant collection temperature modes. Applied Energy 86, 2592–2597. https://doi.org/10.1016/j.apenergy.2009.04.004

Tiwari, A., Sodha, M.S., 2006. Performance evaluation of solar PV/T system: An experimental validation. Solar Energy 80, 751–759. https://doi.org/10.1016/j.solener.2005.07.006

Zhao, J., Li, Z., Ma, T., 2019. Performance analysis of a photovoltaic panel integrated with phase change material. Energy Procedia 158, 1093–1098. https://doi.org/10.1016/j.egypro.2019.01.264