Erzincan Üniversitesi
Fen Bilimleri Enstitüsü Dergisi
2022, 15(1), 340-359
ISSN: 1307-9085, e-ISSN: 2149-4584
Araştırma Makalesi

Erzincan University
Journal of Science and Technology
2022, 15(1), 340 - 359
DOI: 10.18185/erzifbed.971321
Research Article

Energy, Exergy and Sustainability Indicators of Photovoltaic Panel Cooling under Forced Convection

Fatih BAYRAK [1*]

[1] Department of Mechanical Engineering, Faculty of Engineering, Siirt University, 56100, Siirt Turkey
Geliş / Received:14/07/2021, Kabul / Accepted: 10/12/2021

Abstract
Photovoltaic (PV) panels generate some of their energy as waste heat while converting solar radiation into electricity. This heat in photovoltaic panels adversely affects the output parameters of the panels. For this reason, there are many studies on cooling of PV panels in the literature. In this experimental study, waste heat was removed by placing DC fans with different numbers and different consumption power on 80 W monocrystalline panels. According to the results obtained from the experiments, while the net power of the reference panel was 62.42W, the net power of the E4 system (with 4 fans and the consumption power of the fans was 10W) was measured as 64.1W. The highest exergy efficiency and sustainability index values among all systems were also obtained from the E4 system.

Keywords: Energy, exergy, DC fan, forced convection, photovoltaic, sustainability.

Zorlanmış Taşınım Altında Fotovoltaik Panel Soğutmasının Enerji, Ekserji ve Sürdürülebilirlik Göstergeleri

Öz

Fotovoltaik (PV) paneller, güneş ışınımını elektriğe dönüştürürken enerjilerinin bir kısmını atık ısı olarak üretir. Fotovoltaik panellerdeki bu ısı, panellerin çıkış parametrelerini olumsuz etkiler. Bu nedenle literatürde PV panellerin soğutulması ile ilgili birçok çalışma bulunmaktadır. Bu deneysel çalışmada, 80 W monokristal paneller üzerine farklı sayıda ve farklı tüketim gücüne sahip DC fanlar yerleştirilerek atık ısı uzaklaştırılmıştır. Deneylerden elde edilen sonuçlara göre referans panelinin net gücü 62.42W iken, E4 sisteminin net gücü (4 fanlı ve fanların tüketim gücü 10W) 64,1W olarak ölçülmüştür. Tüm sistemler arasında en yüksek ekserji verimliliği ve sürdürülebilirlik indeks değerleri de E4 sisteminden elde edilmiştir.

Anahtar Kelimeler: Enerji, ekserji, DC fan, zorlanmış taşınım, fotovoltaik, sürdürebilirlik.

1. Introduction

The rapid progress of industrialization and the increase in the world population day by day increase the world's demand for energy. However, the energy crisis is an obstacle to economic growth in many countries. One of the most effective ways to solve these problems is to reduce fossil fuel consumption and replace it with more renewable energy systems (Cuce et al., 2013; Shukla et al., 2017). The source of renewable energy systems is the sun and radiation from the sun can be converted into electricity and thermal energy using photovoltaic (PV) panels and thermal collectors. The efficiency of solar thermal systems is between 40% and 60% while the efficiency of PV panels varies between 10% and 20% (Bashir et al., 2018; Wang et al., 2019). As in every system, it is desirable for PV panels to work efficiently. There are many factors that can reduce the efficiency of the PV panel, and they are classified as cell materials, PV system devices and environmental factors (Idoko et al., 2018). Some of it emerges as heat energy while some of the radiation coming from the sun in PV panels is converted into electrical energy. This situation causes the PV panel to heat up and while the short circuit current (I_{sc}) of the panels increases, the open circuit voltage (V_{oc}) decreases (Bayrak, et al., 2017; Tiwari et al., 2011). In addition, the temperature distribution of the solar cells that make up the PV panel is not uniform, which creates hot spots on the PV panels. (Bahaidarah et al., 2016). Thermocouples were placed on the back surface of an uncooled PV panel at 10 different points, and the lowest and highest temperatures were measured as 46.32 °C and 51.54 °C, respectively (Bayrak et al., 2019). This experimental study confirms that the temperature distribution on the PV panel surface is not uniform. Non-uniform temperature distribution causes a decrease in efficiency in the short term and permanent structural defects with thermal stresses in the long term. Therefore, it plays a vital role in the cooling operation and system cost of PV panels.

In cases where the cell temperature, which can directly affect the performance of the PV panels, cannot be reduced sufficiently under natural conditions with the outdoor temperature, different solution proposals have been developed to increase the efficiency of the photovoltaic panel. Cooling methods, which can generally be classified as active or passive, reduce the temperature of the cell surface and increase the performance of the photovoltaic panel (Bahaidarah et al., 2016; Sudhakar et al., 2017). It has been observed that active cooling methods are more effective than passive cooling methods. However, considering the material types used, investment cost and cost effectiveness, it has been stated that passive methods can be applied more practically (Elbreki et al., 2017; Hasanuzzaman et al., 2016).

In the literature, many studies are carried out to reduce the panel back surface temperature in order to prevent the temperature increase that reduces the output parameters of the PV panels. Efficiency, evaluation of waste heat, economic status and technological aspects of PV panels cooled with different cooling methods were evaluated and classified by (Siecker et al., 2017) and (Siah Chehreh Ghadikolaei, 2021). They stated that air-cooled systems are not as efficient as water-cooled systems, PV panels cooled using thermoelectricity are developing technologically, the heat absorption capacity of PCM systems decreases over time, and climatic conditions are effective. The cooling of PV panels and their effects on performance are discussed in detail by (Makki et al., 2015) using different thermal management techniques such as water cooling, heat pipes, thermoelectric, phase change materials (PCM), natural and forced convection. Bayrak et al. (Bayrak, et al., 2017) were studied a review on the exergy efficiency of PV, PV/T collectors (air and water) and concentrating solar power systems. The positive effects of exergy analyze on the environment and economy are mentioned while explaining the cause of the losses in energy systems.

Irwan et al. (Irwan et al., 2015) used two different cooling systems to increase the output power of PV panels and compared them with uncooled PV panels. When the output power of cooled systems is compared with uncooled PV panels; There was an increase of 32.23% in the system cooled by DC fan and 38.98% in the system cooled by DC water pump. In addition, the surface temperatures of the panels were reduced by 6.1 °C and 6.36 °C, respectively, by using the fan and pump. Amelia et al. (Amelia et al., 2016) were investigated experimentally the effects of different numbers of DC fans integrated into PV panels on cooling and output power As the number of fans in the cooling system increased, the output power obtained from the panels also increased. As a result, systems with 2, 3 and 4 fans increased the output power of the PV panel by 37.17%, 41.28% and 44.34%, respectively. Syafiqah et al. (Syafiqah et al., 2017) modeled the temperatures and output powers of cooled and uncooled PV systems with different number of DC fans in their simulation. The net output powers of the systems are 64.7W, 67.08W, 67.56W, 67.34W and 67.32W for PV, PV with 1 DC fan, PV with 2 DC fans, PV with 3 DC fans and PV with 4 DC fans, respectively. Syafiqah et al. (Syafiqah et al., 2017) numerically investigated the effect of DC fans with 6 different power and flow rates on the net output power and surface temperature of the PV panels. The flow rates and power consumption of the fans are 1.99 m/s-4.49 m/s and 0.72 W-4.80W, respectively. According to the results obtained, the highest output power and the lowest surface temperature were realized at the highest DC fan speed (4.99 m/s). However, the system with a speed of 3.07 m/s and power consumption of 1.08 W gave the highest net output power. Arifin et al. (Arifin et al., 2020) investigated the effect of aluminum fin integrated PV panels on temperature and output power under forced convection. In the case of 1.5 m/s air flow rate, 35 °C ambient temperature and 1000 W/m^2 solar radiation, the surface temperature of the cooled and uncooled PV panels increased by approximately 13 °C and the output power increased by 18.67%. Bevilacqua et al. (Bevilacqua et al., 2020, 2021) were investigated temperature distribution, output power, electrical efficiency and economic analysis of spray and DC fan cooling systems and uncooled PV panels The performance of each cooling system outperformed the uncooled system. When the economic analysis is examined, they stated that the spray cooling system (PV3) pays the initial investment cost in a shorter time than the others. Fudholi et al. (Fudholi et al., 2019) studied exergy analyzes of solar collectors, drying systems and PV/T collectors in this study. In addition, the exergy, energy efficiency and sustainability index of the PV/T system with a ∇-slot absorber were investigated. At the end of the experimental studies, the exergy efficiency of the PV/T system was found to be 13.36% and the sustainability index was found to be 1.148.

The relationship between the output parameters of the panels and the temperature was examined by using different cooling types in PV panels when the literature is examined. Cooling types are divided into active and passive systems, and the consumption power of the pump or fan used in active cooling systems is calculated and its effect on system efficiency is examined very little. In this experimental study, the missing parts of the researchers who previously studied the cooling of PV panels with DC fan were filled. The original aspects of the study can be listed as follows; The effect of DC fan power and optimum DC fan number on cooling, obtaining net power by calculating fan power, evaluating the energy and exergy efficiencies of the system using net power, and finally, the analysis of exergy values and sustainability indicators were interpreted.

2. Material and Method

The experiments were carried out in Siirt province of Turkey, which has hot climatic conditions. Average temperatures in June, July and August are 30 °C for Turkey and 38 °C for the city of Siirt (*Https://Www.Worlddata.Info/*, 2021). Experiments were carried out in the form of serial experiments on clear days in August 2020. The experimental set was set up in the backyard of Siirt University Engineering Faculty. In Figure 1 are shown the pictures of the experiment set while the connection type of the cooling system and the devices in the measurement station is schematized in Figure 2. The layout plans of the DC fans is shown in Figure 3.

The aim of this study is to investigate the effect of DC fan cooling systems on PV panels in climates where solar radiation value and ambient temperature are very high, as well as low wind speed. The technical specifications of the DC fan and PV panel used in the experiments are given in Table 1. DC fans have been preferred as a cooling unit due to their simple structure compared to AC fans, less cost and less power consumption. Detailed explanations of the cooling systems are given in Table 2.

In order to calculate which of the cooling systems has the better performance, some values need to be measured. These values are; environmental temperature, PV panel (cell) temperature, local solar radiation, maximum current (I_m) and voltage (V_m) values, wind speed and fan speed. The ambient temperature and the back surface temperature of the PV panels were measured using T-type thermocouples. Thermocouples are Omega brand and accuracy is ±0.1 °C. Solar radiation values were read in W/m^2 with MS-402 model pyranometer. The sensitivity of the device is 7 μV/(W·m^{-2}) and accuracy is <6 W/m^2. The CEM-DT-619 anemometer was used for measuring the air velocity and its sensitivity is given as ±0.2 m/s. The KEITHLEY 701 brand 40-channel data compiler was used to measure the voltage values at the same time (current accuracy ±0.9%, voltage accuracy ±0.5%, resistance accuracy ±0.7%).

(a) (b)

Figure 1. Views of the experimental setup (a) from behind (b) front

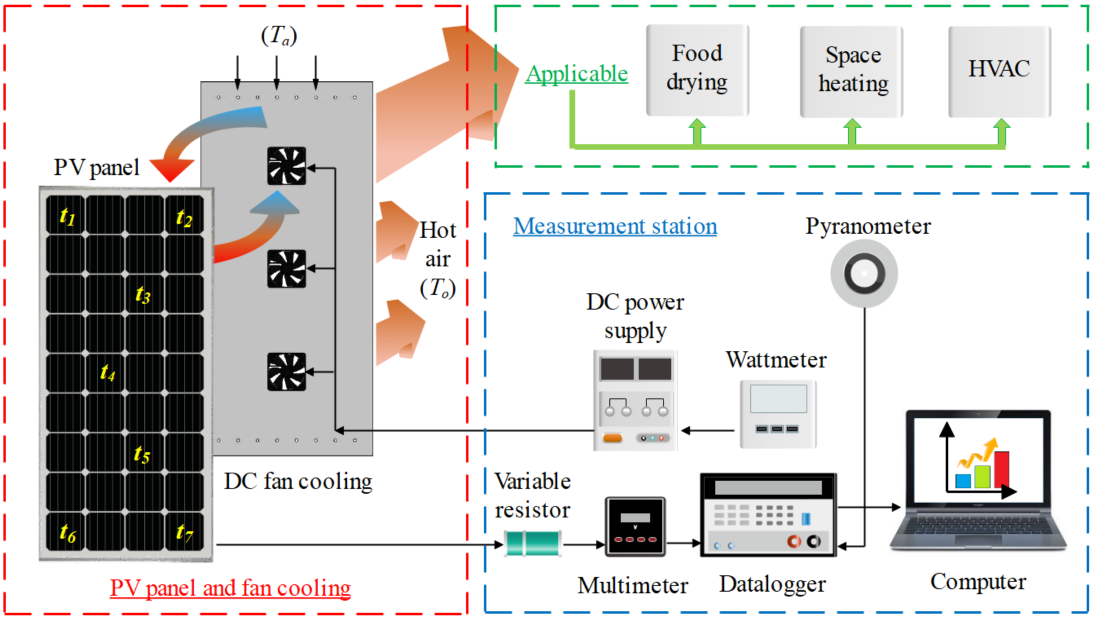

Figure 2. The schematic view of the experimental setup

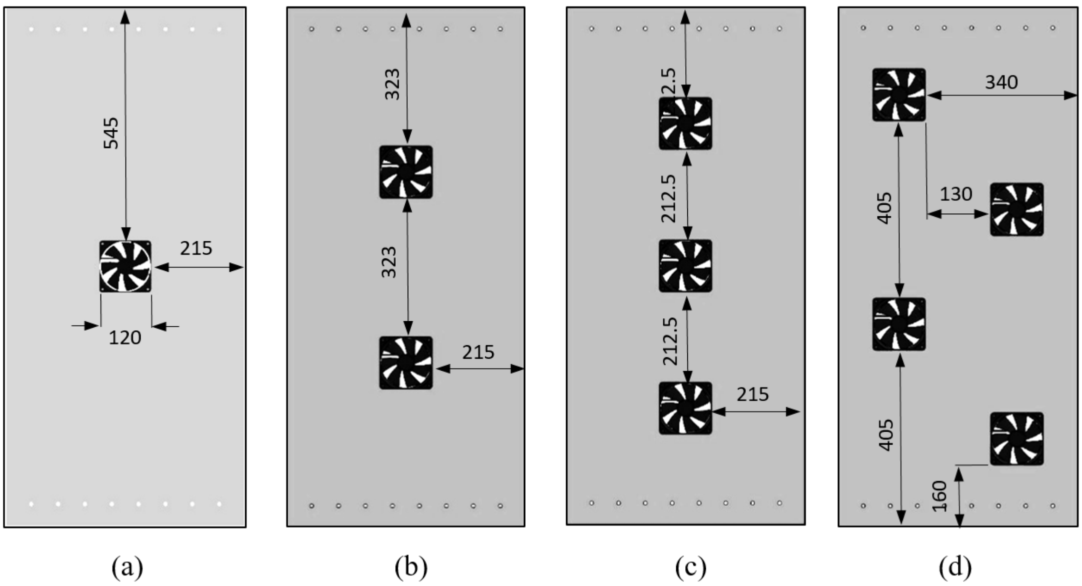

Figure 3. Layout plans of DC fans placed behind the PV panel (a) with 1 DC fan (b) with 2 DC fan (c) with 3 DC fan and (d) with 4 DC fan

Table 1. Technical specifications of PV panels and DC fans (*Inko*, 2020; Lorentz, 2020)

Parameters	**Values**
PV panel	
Maximum power (P_m)	80 W
Open circuit voltage (V_{oc})	22.4 V
Max. power voltage (V_m)	17.2
Short circuit current (I_{sc})	5 A
Max. power current (I_m)	4.6
Tolerance of the rating power	±%5
Temperature Coefficients of I_{sc}	0.09 %/°C
Temperature Coefficient of V_{oc}	-0.35%°C
Temperature Coefficient of P_m	-0.50%°C
Dimensions	550x1210x35 mm
Cell technology	Monocrystalline
DC fan	
Operating voltage	12 V
Operating current	0.25 A
Revolutions Per Minute (RPM)	2200 ±%10

Table 2. Classification of PV systems

Case	Part	Number of fans	Fan power consumption (W)	Case	Part	Number of fans	Fan power consumption (W)
Ref.	-	-	-	D	D1	3	2
					D2	3	3
B	B1	1	1		D3	3	6
	B2	1	2		D4	3	9
	B3	1	3		D5	3	10
				E	E1	4	2
C	C1	2	1		E2	4	3
	C2	2	2		E3	4	6
	C3	2	3		E4	4	9
					E5	4	10

2.1.Analysis

2.1.1. Power analysis

The maximum electrical output power of a PV panel is calculated using the formula below (Shmroukh, 2019):

$$P_m = I_m V_m$$
(1)

where V_m and I_m are the maximum power voltage and maximum power current, respectively. The power of the cooling fans and the net power (P_{net}) obtained from the PV panels are calculated using the formulas below (Gholampour et al., 2014; Wang et al., 2019):

$$P_{fan} = I_{fan} V_{fan}$$
(2)

$$P_{net,cooloed} = P_m - P_{fan}$$
(3)

$$P_{net,uncooloed} = P_m$$

(4)

where V_{fan}, I_{fan}, P_{fan} are the voltage, current and power values of the fan under load, respectively. P_{net} is equal to P_m as no fan is used in the uncooled system.

2.1.2. Energy and exergy analysis

The first law of thermodynamics states that energy can change from one form to another, but the total amount of energy remains constant (Dincer & Cengel, 2001). The Second Law of Thermodynamics states that processes will occur in a particular direction, not in any one direction. Accordingly, exergy analysis; It plays an important role in the design and development of systems as it can accurately determine the location, type and amount of exergy destructions and losses. Exergy efficiency, on the other hand, is an indicator of how close a system or the process under consideration is to ideal conditions. In addition, by reducing the thermodynamic inefficiencies in the system or process handled with this method, it provides how to design a more efficient system and define the current conditions correctly (Dincer, 2002).

The energy efficiency of the PV panel is expressed as (Akyuz et al., 2012; Bayrak et al., 2019).

$$\eta_I = \frac{\dot{E}_{out}}{\dot{E}_{in}} = \frac{P_m}{I_s A}$$

(5)

Considering the use of DC fans in the system, the effective efficiency or overall efficiency of the PV panel system is expressed as: (Gholampour et al., 2014; Shmroukh, 2019; Wang et al., 2019).

$$\eta_{I,sys} = \frac{P_m - P_{fan}}{I_s A}$$

(6)

The exergy input of a PV system is calculated using the following formula (Petela, 2008):

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

(7)

where T_s is the temperature of sun which is taken as 5777 K. The exergy output and exergy power of the photovoltaic systems can be expressed as follows (Bayrak et al., 2020; Wang et al., 2019)

$$\dot{E}x_{out} = \dot{E}x_{electric}$$

(8)

$$\dot{E}x_{electric} = P_m = I_m V_m$$

(9)

$$\eta_{II} = \frac{\left(P_m - P_{fan}\right)}{I_s A\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right]}$$

(10)

2.1.3. Exergetic sustainability indicators

In order to better evaluate the thermodynamic performance of the systems, it is necessary to examine the sustainability indicators that deal with exergy values. The exergy loss per given exergy input, the recovery ability and life of the system can be evaluated by WER, IP and SI values, respectively. By analyzing these indicators, an optimum cooling can be easily designed by reducing the irreversibility in the PV cooling system. Exergetic sustainability indicators are calculated from the following equations (Bayrak et al., 2013; Hammond and Stapleton, 2001; Ndukwu et al., 2017, 2020; Oztop et al., 2013):

$$IP = \left(1 - \eta_{II}\right)\left(\dot{E}x_{in} - \dot{E}x_{out}\right)$$

(11)

$$WER = \frac{\dot{E}x_{loss}}{\dot{E}x_{in}}$$

(12)

$$SI = \frac{1}{1 - \eta_{II}}$$

(13)

2.1.4. Uncertainty analysis

The fact that experimental studies are based on a measurement system has always been ahead of numerical and analytical studies in terms of realism. However, the error and uncertainty of the measured values in experimental studies are very important. The analysis applied to determine these errors and uncertainties is called “Uncertainty Analysis”. Uncertainty analysis should be applied both in the interpretation of the experimental results and in the design studies before the system installation (Bayrak and Oztop, 2020; Hepbasli and Akdemir, 2004).

In order to determine the accuracy of the calculated parameters, it is necessary to determine the uncertainties of the measured values. On condition that a dependent variable (R) is presented, which affected by some of the independent variables (x_1; x_2; x_3;…; x_n), its uncertainty value (W_R) can be estimated using the equation below (Holman, J.P., 1994; Selimefendigil et al., 2018). The uncertainty values calculated can be seen in Table 3.

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

(14)

Table 3. Uncertainty analysis of measured values

Parameters	**Unit**	**Result**
Ambient temperature	^{o}C	±0.925
PV panel temperature	^{o}C	±0.925
Air velocity	ms^{-1}	±0.24
Solar radiation	Wm^{-2}	±0.096
Voltage measurement	V	±0.0075
Current measurement	A	±0.0091
PV power	W	±0.849
DC fan power	W	±0.17

3. Result and Discussion

In this study, electrical values, energy and exergy values of PV panels were analyzed by using DC fans with different numbers and different power consumptions. In addition, exergetic sustainability indicators of all experimental studies were examined. Experiments were tested sequentially on days when the weather was not cloudy. In Figure 4, the maximum values of output powers and net output powers values of cooled and uncooled PV panels are given. The P_m and P_{net} values produced by the reference PV panel were measured as 62.42 W when Figure 4 is examined. The red and dashed line in Figure 4 shows the output power produced by the reference panel. In addition, this line will help us to evaluate the output power of PV panels in all cooling conditions applied in this study. In Figure 4, the P_m and P_{net} values produced by the PV panels in the B1, C1, D1 and E1 cases are lower than the power produced by the reference panel. The reason for this is that the back surface of the cooling panels is covered with a metal surface, so more heat accumulation has occurred on the back surface of the PV panels. Due to insufficient fan number and fan speed, the temperature on the back surface of the cooled PV panels (B1, C1, D1 and E1) was higher than the surface temperature of the reference panel. Looking at Table 1, it is seen that the temperature coefficient of the output power of the PV panels has a negative value. As the number of fans and fan speed increase, the P_m values of the PV panels increase up to 12 W, but when the power consumed by the fans is subtracted from the power produced by the PV panels, critical decreases have occurred in the P_{net} values. As a result, the net power (P_{net}) produced by the reference panel is 62.42 W, and in the case of E4 it is 64.1 W.

In Figure 5, the variation of the energy and overall efficiency values of the systems with 1 and 2 DC fans placed on the PV panel and the uncooled (reference) panel according to time are given. In Figure 4 (a), the efficiency values of B1 and C1 cases were below the efficiency value of the reference panel. The reason for this was that the heat formed on the back surface of the panel could not be discharged sufficiently by the DC fans, which had a negative effect on the efficiency. In Figure 4 (b), although the energy efficiency value of the C2 case was higher than the reference panel, the overall efficiency value remained below the overall efficiency value of the reference panel. In Figure 4 (c), the increase in the speed of the DC fan has a positive effect on the cooling of the PV panel. The energy efficiency of reference PV, B3 and C3 systems is 9.18%, 9.65% and 9.90%, respectively. The overall efficiencies of these systems are 9.18%, 9.19% and 9.44%, respectively. When Figure 5 is evaluated in general, the reason why the efficiency values of some fan-cooled cases (B1, B2 and C1) are lower than the uncooled condition (reference) is that the number of fans and their speeds are insufficient. For these reasons, the PV panel surface temperature caused a higher temperature than the reference situation. In this experimental study, it is aimed to optimize the waste heat removal on PV panels by using DC fans in PV panels.

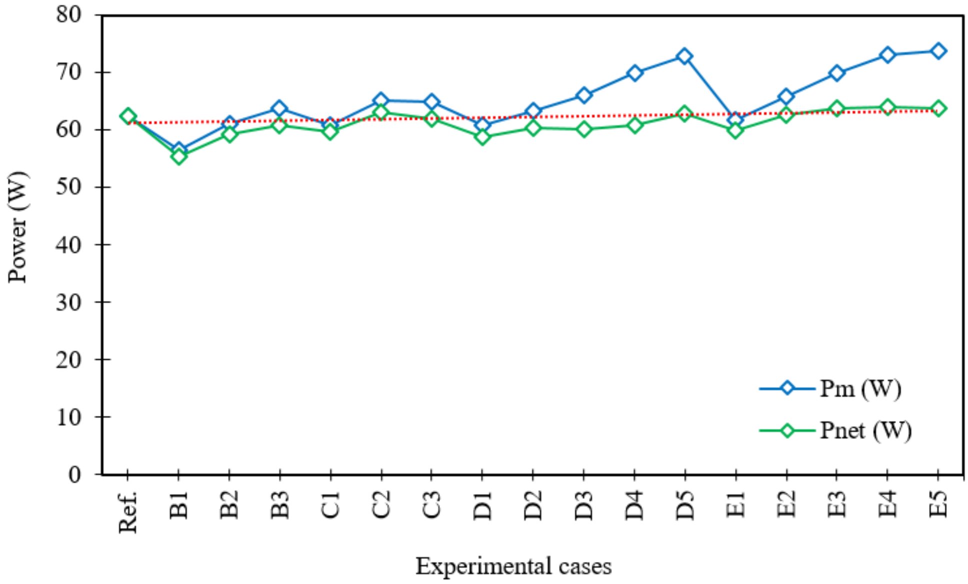

Figure 4. Electrical values of cooled and uncooled PV panels

The temperature coefficient of PV panels will give information about the variation of panel power with temperature. It is important to pay attention to the temperature coefficient in the selection of PV panels, but it is definitely not enough. Because efficiency; It depends on many parameters such as wind speed, ambient temperature, panel surface temperature, panel surface area, cell temperature, radiation intensity, placement of panels. The efficiency values in the first parts (B1, C1, D1 and E1) of all cases (B, C, D and E) in the experimental study were lower than the efficiency value of the reference panel when Figure 6 is examined. The reason for this is that no matter how much the number of fans increases, the airflow passing through the back surface of the PV panel is insufficient and causes more heating instead of cooling, thus reducing both output power and efficiency (energy and exergy) values.

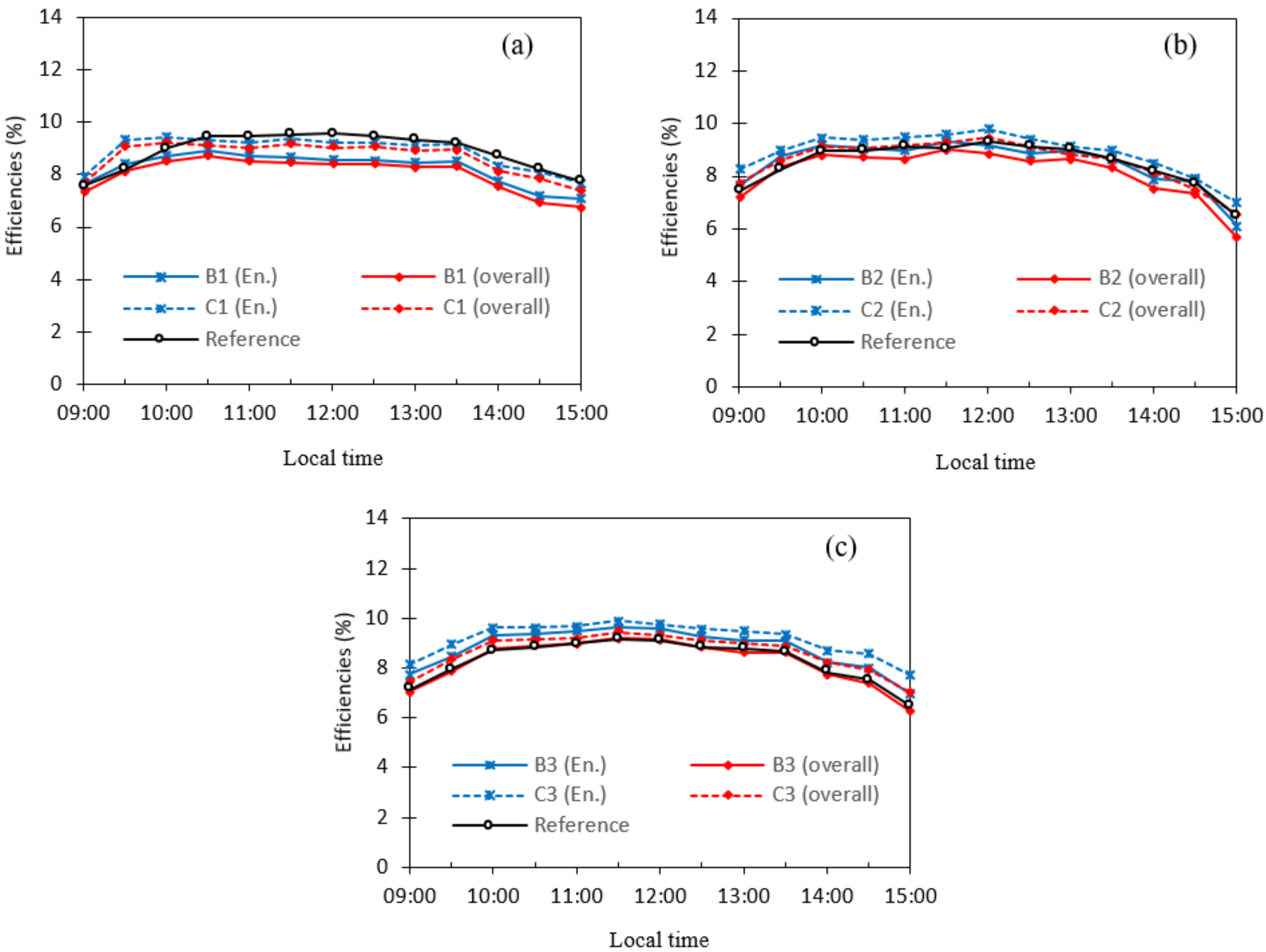

Figure 5. Efficiency values of PV panels with 1 and 2 DC fans

In Figure 6, the comparison of D and E cases with 3 and 4 DC fans with uncooled PV panels is given. It is seen in Figure 5 (a and b) that the number of revolutions of DC fans is insufficient to cool the PV panels, and in Figure 5 (c, d and e), DC fans have a positive effect on cooling. In Figure 5(c), the maximum overall efficiency values of the reference, D3 and E3 panels are 9.59%, 9.63% and 10.38%, respectively. In Figure 5 (d), the maximum overall efficiency values of the reference, D4 and E4 panels are 9.52%, 9.48% and 10.12%, respectively. In Figure 5 (e), the maximum overall efficiency values of the reference, D5 and E5 panels are 9.38%, 9.69% and 9.87%, respectively.

The lowest and highest exergy output, exergy loss, exergy efficiency, IP, SI and WER values of cooled and uncooled PV panels are given in Table 4. With the positive effect of the cooling systems, the output exergy of the photovoltaic panels increased and the exergy loss decreased. This situation also had a positive effect on the exergy efficiency. While the highest exergy efficiency of the reference PV panel was 9.03%, the highest exergy efficiency of the E4 system was calculated as 12.47%. While the sustainability index was 1.148 in the results of Fudholi et al. (Fudholi et al., 2019) on PV/T collectors, it was 1.249 in the current study (E4). Since the IP and WER values are directly related to the exergy losses, as the mass flow rate of the air in the DC fans increases, the temperature drop and exergy losses of the PV panels decrease. This explains that the IP and WER values are lower especially in the E4 system compared to the reference PV panel.

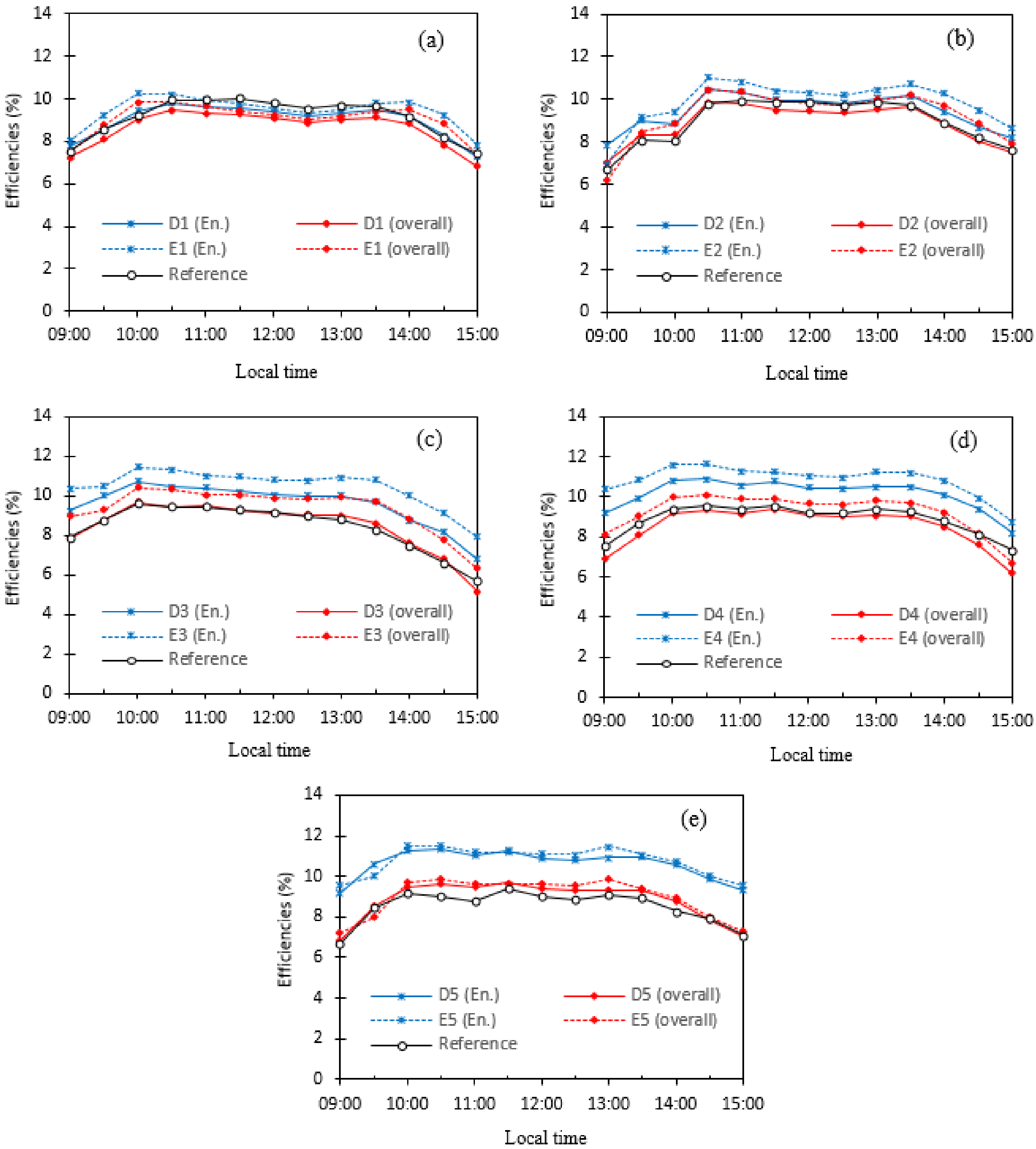

Figure 6. Efficiency values of PV panels with 3 and 4 DC fans

Table 4. Exergy and sustainability values of DC fan cooled and uncooled PV panels

		Exergy values			**Sustainability Indicators**		
Cases	**Low / High**	**Exergy output (W)**	**Exergy loss (W)**	**Exergy efficiency (%)**	***IP* *(W)***	***SI***	***WER***
Ref.	*Low*	*24.40*	*345.16*	*6.60*	*322.37*	*1.071*	*0.871*
	High	*56.06*	*559.58*	*9.30*	*508.98*	*1.103*	*0.929*
B1	Low	21.32	375.01	5.38	354.82	1.057	0.922
	High	45.70	566.19	7.82	525.95	1.085	0.946
B2	Low	20.30	361.73	4.72	336.93	1.050	0.917
	High	49.99	573.48	8.26	528.32	1.090	0.953
B3	Low	23.42	342.72	5.70	317.82	1.060	0.908
	High	56.44	558.77	9.17	507.51	1.101	0.943
C1	Low	23.86	372.47	6.02	350.04	1.064	0.916
	High	49.11	561.89	8.37	517.97	1.091	0.940
C2	Low	24.90	359.45	5.79	332.67	1.061	0.914
	High	52.87	570.65	8.55	523.11	1.094	0.942
C3	Low	25.77	340.92	6.27	314.50	1.067	0.906
	High	57.78	557.43	9.42	505.08	1.104	0.937
D1	Low	23.93	309.52	7.03	287.32	1.076	0.901
	High	57.82	546.41	9.82	495.93	1.109	0.923
D2	Low	25.82	318.89	7.49	295.00	1.081	0.894
	High	59.96	538.83	10.56	484.86	1.118	0.925
D3	Low	19.59	332.10	5.57	313.59	1.059	0.896
	High	60.01	539.14	10.35	486.29	1.115	0.944
D4	Low	27.33	342.23	7.39	316.92	1.080	0.883
	High	69.80	545.80	11.66	484.33	1.132	0.926
D5	Low	28.57	367.66	7.21	341.14	1.078	0.897
	High	62.10	549.69	10.31	498.09	1.115	0.928
E1	Low	24.86	308.59	7.45	285.58	1.081	0.897
	High	58.17	546.76	10.26	496.58	1.114	0.925
E2	Low	22.29	322.42	6.49	301.56	1.069	0.889
	High	62.11	536.71	11.10	481.04	1.249	0.935
E3	Low	23.85	327.83	6.78	305.59	1.073	0.889
	High	63.41	534.60	11.09	478.13	1.125	0.932
E4	*Low*	*32.02*	*337.54*	*8.66*	*308.29*	*1.095*	*0.876*
	High	*72.92*	*542.14*	*12.47*	*477.86*	*1.142*	*0.913*
E5	Low	30.53	365.69	7.70	337.51	1.084	0.894
	High	63.65	551.44	10.62	494.37	1.119	0.923

4. Conclusions

In this study. forced convection cooling of PV systems with different DC fan numbers and different DC fan powers was investigated experimentally. Detailed power analyzes. energy efficiency. exergy outputs and sustainability indicators of all systems were examined. The main important findings can be summed as follows:

- The maximum output powers of the PV systems are 73.78 W, 73.1 W and 62.42 W at the E5, E4 and reference panel. respectively.
- The maximum net output powers of the PV systems are 64.1 W, 63.86 W and 62.42 W at the E4, E3 and reference panel. respectively.
- Performance ratios are 0.791 for the reference panel. 0.866 for the E2 system, 0.863 for the E3 system and 0.841 for the E4 system.
- When the efficiency values of the cases with 1 and 2 DC fan systems (B1-B3 and C1-C3) according to the PV panel sizes used in the experiments were examined. It did not have a positive effect on the cooling of the PV panels.
- The highest values were calculated as 10.38% and 10.12% in E3 and E4 cases when the overall efficiency values of all systems were compared.
- The highest exergy efficiency and sustainability index were obtained from the E4 case with 12.1% and 1.137%. respectively.

Nomenclature

A	area of PV (m^2)
Ex	Exergy (W)
h_{ca}	heat transfer coefficient (W/m^2K^{-1})
I	current (A)
I_s	solar radiation (W/m^2)
I_{sc}	short circuit current (A)
P	power (W)
$\dot{Q}$	heat emitted to the surrounding (W)
T	temperature (^oC)
V	voltage (V)
V_{oc}	open circuit voltage (V)
v	wind velocity (m/s)
η_I	energy efficiency
η_{II}	exergy efficiency

Subscripts

a	ambient
c	cell
m	maximum
s	sun
sys	system

Abbreviations

IP Improvement Potential
PV Photovoltaic
SI Sustainable Index
WER West Exergy Ratio

Ethics in Publishing

There are no ethical issues regarding the publication of this study.

References

Akyuz, E., Coskun, C., Oktay, Z., & Dincer, I. (2012). A novel approach for estimation of photovoltaic exergy efficiency. Energy, 44(1), 1059–1066. https://doi.org/10.1016/j.energy.2012.04.036

Amelia, A. R., Irwan, Y. M., Irwanto, M., Leow, W. Z., Gomesh, N., Safwati, I., & Anuar, M. A. M. (2016). Cooling on photovoltaic panel using forced air convection induced by DC fan. International Journal of Electrical and Computer Engineering, 6(2), 526–534. https://doi.org/10.11591/ijece.v6i1.9118

Arifin, Z., Tjahjana, D. D. D. P., Hadi, S., Rachmanto, R. A., Setyohandoko, G., & Sutanto, B. (2020). Numerical and experimental investigation of air cooling for photovoltaic panels using aluminum heat sinks. International Journal of Photoenergy, 2020. https://doi.org/10.1155/2020/1574274

Bahaidarah, H. M. S., Baloch, A. A. B., & Gandhidasan, P. (2016). Uniform cooling of photovoltaic panels: A review. Renewable and Sustainable Energy Reviews, 57, 1520–1544. https://doi.org/10.1016/j.rser.2015.12.064

Bashir, M., Ali, H., Amber, K., Bashir, M., Ali, H., Imran, S., & Kamran, M. (2018). Performance investigation of photovoltaic modules by back surface water cooling. Thermal Science, 22(6 Part A), 2401–2411. https://doi.org/10.2298/TSCI160215290B

Bayrak, F., Oztop, H. F., & Hepbasli, A. (2013). Energy and exergy analyses of porous baffles inserted solar air heaters for building applications. Energy and Buildings, 57. https://doi.org/10.1016/j.enbuild.2012.10.055

Bayrak, F., Abu-Hamdeh, N., Alnefaie, K. A., & Öztop, H. F. (2017). 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. (2017). 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., and Oztop, H. F. (2020). Effects of static and dynamic shading on thermodynamic and electrical performance for photovoltaic panels. Applied Thermal Engineering, 169(January), 114900. https://doi.org/10.1016/j.applthermaleng.2020.114900

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

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(February), 112789. https://doi.org/10.1016/j.enconman.2020.112789

Bevilacqua, P., Bruno, R., & Arcuri, N. (2020). Comparing the performances of different cooling strategies to increase photovoltaic electric performance in different meteorological conditions. Energy, 195, 116950. https://doi.org/10.1016/j.energy.2020.116950

Bevilacqua, P., Perrella, S., Cirone, D., Bruno, R., & Arcuri, N. (2021). Efficiency Improvement of Photovoltaic Modules via Back Surface Cooling. Energies, 14(4), 895. https://doi.org/10.3390 /en14040895

Cuce, E., Cuce, P. M., & Bali, T. (2013). An experimental analysis of illumination intensity and temperature dependency of photovoltaic cell parameters. Applied Energy, 111, 374–382. https://doi.org/10.1016/j.apenergy.2013.05.025

Dincer, I. (2002). The role of exergy in energy policy making. Energy Policy, 30(2), 137–149. https://doi.org/10.1016/S0301-4215(01)00079-9

Dincer, I., & Cengel, Y. A. (2001). Energy, entropy and exergy concepts and their roles in thermal engineering. In Entropy (Vol. 3, Issue 3). https://doi.org/10.3390/e3030116

Elbreki, A. M., Alghoul, M. A., Sopian, K., & Hussein, T. (2017). Towards adopting passive heat dissipation approaches for temperature regulation of PV module as a sustainable solution. Renewable and Sustainable Energy Reviews, 69(September), 961–1017. https://doi.org/10.1016/ j.rser.2016.09.054

Fudholi, A., Zohri, M., Rukman, N. S. B., Nazri, N. S., Mustapha, M., Yen, C. H., Mohammad, M., & Sopian, K. (2019). Exergy and sustainability index of photovoltaic thermal (PVT) air collector: A theoretical and experimental study. Renewable and Sustainable Energy Reviews, 100(July 2018), 44–51. https://doi.org/10.1016/j.rser.2018.10.019

Gholampour, M., Ameri, M., & Sheykh Samani, M. (2014). Experimental study of performance of Photovoltaic-Thermal Unglazed Transpired Solar Collectors (PV/UTCs): Energy, exergy, and electrical-to-thermal rational approaches. Solar Energy, 110, 636–647. https://doi.org/10.1016/j.solener.2014.09.011

Hammond, G. P., & Stapleton, A. J. (2001). Exergy analysis of the United Kingdom energy system. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 215(2), 141–162. https://doi.org/10.1243/0957650011538424

Hasanuzzaman, M., Malek, A. B. M. A., Islam, M. M., Pandey, A. K., & Rahim, N. A. (2016). Global advancement of cooling technologies for PV systems: A review. Solar Energy, 137, 25–45. https://doi.org/10.1016/j.solener.2016.07.010

Hepbasli, A., & Akdemir, O. (2004). Energy and exergy analysis of a ground source (geothermal) heat pump system. Energy Conversion and Management, 45(5), 737–753.

https://doi.org/ 10.1016/S0196-8904(03)00185-7

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

https://www.worlddata.info/. (2021). https://www.worlddata.info/, 03.04.2021.

Idoko, L., Anaya-Lara, O., & McDonald, A. (2018). Enhancing PV modules efficiency and power output using multi-concept cooling technique. Energy Reports, 4, 357–369. https://doi.org/10.1016/j.egyr.2018.05.004

inko. (2020). https://www.inkoelektronik.com.tr/urun/120x120x25mm-12vdc, 03.11.2021.

Irwan, Y. M., Leow, W. Z., Irwanto, M., Fareq, M., Hassan, S. I. S., Safwati, I., & Amelia, A. R. (2015). Comparison of solar panel cooling system by using dc brushless fan and dc water. Journal of Physics: Conference Series, 622(1). https://doi.org/10.1088/1742-6596/622/1/012001

Lorentz. (2020). LC80-12M. https://www.deparsolar.com/images/dosya/LC80_12M.pdf, 03.11.2021.

Makki, A., Omer, S., & Sabir, H. (2015). Advancements in hybrid photovoltaic systems for enhanced solar cells performance. Renewable and Sustainable Energy Reviews, 41, 658–684. https://doi.org/10.1016/j.rser.2014.08.069

Ndukwu, M. C., Bennamoun, L., Abam, F. I., Eke, A. B., & Ukoha, D. (2017). Energy and exergy analysis of a solar dryer integrated with sodium sulfate decahydrate and sodium chloride as thermal storage medium. Renewable Energy, 113, 1182–1192. https://doi.org/10.1016/j.renene. 2017.06.097

Ndukwu, M. C., Simo-Tagne, M., Abam, F. I., Onwuka, O. S., Prince, S., & Bennamoun, L. (2020). Exergetic sustainability and economic analysis of hybrid solar-biomass dryer integrated with copper tubing as heat exchanger. Heliyon, 6(2), e03401. https://doi.org/10.1016/j.heliyon. 2020 .e03401

Oztop, H. F., Bayrak, F., & Hepbasli, A. (2013). Energetic and exergetic aspects of solar air heating (solar collector) systems. Renewable and Sustainable Energy Reviews, 21. https://doi.org/10.1016/j.rser.2012.12.019

Petela, R. (2008). An approach to the exergy analysis of photosynthesis. Solar Energy, 82(4), 311–328. https://doi.org/10.1016/j.solener.2007.09.002

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

Shmroukh, A. N. (2019). Thermal regulation of photovoltaic panel installed in Upper Egyptian conditions in Qena. Thermal Science and Engineering Progress, 14(October), 100438. https://doi.org/10.1016/j.tsep.2019.100438

Shukla, A., Kant, K., Sharma, A., & Biwole, P. H. (2017). Cooling methodologies of photovoltaic module for enhancing electrical efficiency: A review. Solar Energy Materials and Solar Cells, 160, 275–286. https://doi.org/10.1016/j.solmat.2016.10.047

Siah Chehreh Ghadikolaei, S. (2021). Solar photovoltaic cells performance improvement by cooling technology: An overall review. International Journal of Hydrogen Energy, 46(18), 10939–10972. https://doi.org/10.1016/j.ijhydene.2020.12.164

Siecker, J., Kusakana, K., & Numbi, B. P. (2017). A review of solar photovoltaic systems cooling technologies. Renewable and Sustainable Energy Reviews, 79(May), 192–203. https://doi.org/ 10.1016/j.rser.2017.05.053

Sudhakar, P., Kumaresan, G., & Velraj, R. (2017). Experimental analysis of solar photovoltaic unit integrated with free cool thermal energy storage system. Solar Energy, 158(October), 837–844. https://doi.org/10.1016/j.solener.2017.10.043

Syafiqah, Z., Amin, N. A. M., Irwan, Y. M., Irwanto, M., Leow, W. Z., & Amelia, A. R. (2017). Performance power evaluation of DC fan cooling system for PV panel by using ANSYS CFX. AIP Conference Proceedings, 1885. https://doi.org/10.1063/1.5002435

Syafiqah, Z., Irwan, Y. M., Amin, N. A. M., Irwanto, M., Leow, W. Z., & Amelia, A. R. (2017). Thermal and Electrical Study for PV Panel With Cooling. Indonesian Journal of Electrical Engineering and Computer Science, 7(2), 492. https://doi.org/10.11591/ijeecs.v7.i2.pp492-499

Tiwari, G. N., Mishra, R. K., & Solanki, S. C. (2011). Photovoltaic modules and their applications: A review on thermal modelling. Applied Energy, 88(7), 2287–2304. https://doi.org/ 10.1016/j.apenergy.2011.01.005

Wang, Y., Gao, Y., Huang, Q., Hu, G., & Zhou, L. (2019). Experimental study of active phase change cooling technique based on porous media for photovoltaic thermal management and efficiency enhancement. Energy Conversion and Management, 199(August), 111990. https://doi.org/10.1016/j.enconman.2019.111990