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Energy, exergy, sustainability, and economic analyses of a grid-connected solar power plant consisting of bifacial PV modules with solar tracking system on a single axis

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Abstract. This study presents the energy, exergy, sustainability and exergoeconomic analysis of a grid-connected solar power plant with a power capacity of 226.4 MWe with a single axis solar tracking system consisting of monocrystalline and bifacial solar panels manufactured with half-cut technology. This solar power plant is located in Karapınar district of Konya province in Türkiye, between 37°45 and 37°47 north latitudes and 33°33 and 33°35 east longitudes. Based on the first and second laws of thermodynamics, the 6-month average values of the energy efficiency, maximum electrical efficiency, power conversion efficiency, exergy efficiency, sustainability index, thermoeconomic, and exergoeconomic parameters of the power plant were evaluated in detail. As a result of the energy and exergy analyses, the energy efficiency, maximum electricity efficiency, power conversion efficiency, and exergy efficiency of the plant were found to be 75.50%, 36.42%, 22.34%, and 21.98%, respectively. The sustainability index of the power plant is 1.29. Thermoeconomic and exergoeconomic parameter values were calculated as 2.43 W/$ and 2.32 W/$, respectively, using EXCEM method.

Keywords: Solar energy, Solar power plant, Exergy, Sustainability, Exergoeconomic analysis.

Nomenclature

I_{sc}	Short circuit current, A
V_{oc}	Open circuit voltage, V
V_{max}	Maximum voltage, V
I_{max}	Maximum current. A
P_{max}	Maximum power, W
E_n	Energy, W
$E_{\dot{x}}$	Exergy, W
$\dot{E}_{x^{output}}$	Output exergy, W
$\dot{E}_{x^{input}}$	Input exergy, W
$\dot{E}_{x^{PV}}$	Photovoltaic exergy, W
$\dot{E}_{x^{solar}}$	Solar exergy, W
S_T	Total solar radiation, W/m^2
h_{ca}	Convective and radiative heat transfer coefficient, m/s
A	Surface area, m^2
$\dot{Q}$	Thermal energy, W
v	Wind velocity, m/s
T_{cell}	Cell temperature, K
T_{amb}	Ambient temperature, K
T_{ec}	Temperature coefficient of V_{oc}, °C
T_{sun}	Sun temperature, K
$\dot{R}_{en}$	Thermoeconomic analysis parameter, W/$
$\dot{R}_{ex}$	Exergoeconomic analysis parameter, W/$
$\dot{L}_{en}$	Energy loss rate, W
$\dot{L}_{ex}$	Exergy loss rate, W
K	Capital cost, $

Acronyms

PV	Photovoltaic
PV/T	Photovoltaic Thermal
SI	Sustainability Index
FF	Fill Factor
MPPT	Maximum Power Point Tracking
GES	Solar Power Plant
Wp	Watt Peak
WMS	Weather Monitoring Station

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SCADA	Supervisory Control and Data Acquisition
MWp	Megawatt Peak
MW_e	Megawatt Electric
DC	Direct Current
AC	Alternating Current
EXCEM	Exergy-Cost-Energy-Mass

Greek symbols

η_{en}	Energy efficiency, %
$\eta_{max,el}$	Maximum electrical efficiency, %
η_{pce}	Power conversion efficiency, %
Ψ	Exergy efficiency, %

1 Introduction

With the development of technology, the need for energy has reached very high levels. However, mankind obtains a large part of its rising energy needs from fossil fuels. Fossil fuels both create environmental problems and are gradually decreasing. This situation has led to a shift towards clean and inexhaustible renewable energy sources. In addition, the Paris Climate Agreement signed by many countries in 2015 aims to produce energy from more environmentally friendly sources rather than fossil fuels. Thus, it is aimed to reduce greenhouse gas emissions. Today, energy production from renewable energy sources and sustainability studies have gained importance.

Photovoltaic systems (PV) can be classified into two types according to their use and application. The first type is systems that can convert solar energy directly into electrical energy through PV modules. The other type is called Photovoltaic thermal (PV/T) systems that use the thermal energy of the sun along with electricity. The thermal energy on the PV surface can be used for low potential tasks such as water and air heating. Photovoltaic applications can be useful in regions where electrical energy is needed and there are sufficient sunshine hours [1]. Solar PV has a wide range of applications due to its versatility and modularity. Solar PV modules can be installed on roofs, walls of buildings, land areas, parking lots and bodies of water [2].

Solar electricity generation is in line with the low emission targets for 2050. Reducing the initial investment cost of conversion systems used in solar electricity generation will be an opportunity for low-cost electricity generation. Efficient use of solar energy systems depends on the reduction of thermal losses. Making the necessary improvements on the system for thermal losses determined by thermodynamic analysis will increase energy efficiency.

Energy and exergy analysis is based on the first and second law of thermodynamics. In energy analysis, only a quantitative evaluation is performed, while in exergy analysis a qualitative evaluation is performed. Exergy is defined as the maximum amount of work that can be produced by a system, substance or energy flow in equilibrium with a reference medium [3]. The reason for the decrease in the exergy of a system is irreversibilities. Increasing irreversibilities decreases exergy efficiency and increases entropy production.

The most common definition of sustainability is "Meeting today's needs without compromising the ability of future generations to meet their own needs." [4]. Sustainability analysis evaluates what and how we use. The sustainability index calculated based on exergy efficiency is important in the evaluation of a system. Exergoeoconomics combines exergy analysis with economic principles, while thermoeconomics combines energy analysis with economic principles. As a result of these exergoeconomic and thermoeconomic analyses, engineering systems are evaluated for higher exergy and energy efficiency and lower unit production costs. They also provide valuable information to system designers or investors that is not available from traditional energy analysis and economic evaluations [5].

Increasing environmental concerns, issues such as climate change and global warming all over the world have made it necessary to generate energy in a more environmentally friendly and clean way. For that reason, scientific studies on renewable energy sources, which are becoming more efficient day by day, have gained significance. Various problems of photovoltaic systems have been answered in the literature. A contribution to the recent literature has been made with the present study on a grid-connected solar power plant located in Karapınar, Konya, Türkiye, consisting of bifacial solar panels and a single-axis solar tracking system.

2 Literature survey

In the literature, there are energy and exergy studies for different purposes in solar power plants. Sahin *et al.* [6] investigated the thermodynamic properties of PV cells. As a result, they found that the energy efficiency of photovoltaic cells varies between 7% and 12% and the exergy efficiency varies between 2% and 8%. They also recommended the use of exergy analysis for more realistic evaluation and planning in photovoltaic cell systems. Joshi *et al.* [3] applied energy and exergy analyses to a PV system for the city of New Delhi in India on March 27, 2006. They found that the exergy efficiency of the PV system varied between 7.8% and 13.8%. Pandey *et al.* [7] determined the performance of a multicrystalline photovoltaic module in northern India by energy and exergy analysis for each different month. According to the results of their study, they determined the average energy, power conversion and exergy efficiencies as 18.09%, 12.26%, 11.17%, respectively. Aoun *et al.* [8] investigated the power conversion, energy and exergy efficiencies of a monocrystalline photovoltaic module in Adrar, Algeria on three different days (March 21–23). On March 21, the weather was cloudy, while on March 22 and 23, the weather was clear. They found that energy, power conversion and exergy efficiencies varied between 17.2% and 22.3%, 12.3% and 16.10%, 5.3% and 12% respectively on cloudy days. On clear days, they found that energy, power conversion and exergy efficiencies varied between 9.28% and 22.1%, 7.55% and 16.83%, 1.8% and 15.5%, respectively. Sudhakar and Srivastava [9] used thermal

Fig. 1. Satellite image of the solar power plant in Karapınar, Konya, Türkiye (Phase-1).

and electrical data of a 36 Watt photovoltaic module and observed that energy efficiency varied between 6% and 9% and exergy efficiency varied between 8% and 10% during the day. Pandey *et al.* [10] conducted energy and exergy performance evaluation on a thin film photovoltaic module on a specific day of each month in northern India. They found that the power conversion efficiency was higher than the exergy efficiency. They also determined that February was the highest in terms of all efficiencies among all months. Sukumaran and Sudhakar [11] performed energy and exergy analysis of a 12 MWp solar power plant located at Cochin international airport in India. As a result of this study, they found that energy efficiency ranged between 13.3% and 16.4% and exergy efficiency ranged between 9% and 10%. Bayat and Ozalp [12] installed a small solar energy system with polycrystalline PV modules on Karabük University Engineering Faculty building (41.12 N, 32.39 W). They performed energy and exergy analysis of this system. According to the results of the analysis, they found that the energy efficiency of the system varies between 24% and 68.4%, maximum electrical efficiency between 12.6% and 23.12%, power conversion efficiency between 9.6% and 18.3%, and exergy efficiency between 9.3% and 18.1%. In addition, as a result of the exergoeconomic analysis they performed on this system, they found that the thermoeconomic analysis parameter varies between 0.06 W/$ and 0.45 W/$ and the exergoeconomic analysis parameter varies between 0.05 W/$ and 0.43 W/$. Bayrak *et al.* [13] applied different blade parameters with different lengths in different arrays to PV modules to show cooling properties on photovoltaic modules in Elazig, Türkiye, and performed energy and exergy analyses. In the results of these experiments, where uncertainty analysis was also applied, the highest energy and exergy efficiency was determined as 11.55% and 10.91%, respectively. Kumar *et al.* [14] evaluated the energy and exergy performance of a 10 MWp grid-connected photovoltaic plant installed on a water canal in Sama, India. They used 2 years of data of the plant for this performance evaluation. They calculated the average performance ratio, system efficiency and exergy efficiency of the plant as 0.78%, 11.90% and 12.03% respectively. Sreenath *et al.* [15] performed 7E analyses at 7 different airports in India. They designed a 5 MW solar power plant for each airport and analyzed it with RETScreen software. According to the results of this study, they concluded that photovoltaic power plants are technically feasible for all airports. Manjunath *et al.* [16] applied energy and exergy analysis to a 50 Watt solar PV module. As a result, they found the maximum values of energy and exergy efficiencies of the PV module to be 25.2% and 32.4%, respectively. Kuczynski and Chliszcz [17] performed energy and exergy analysis of monocrystalline and amorphous PV cells in Northern Poland. They found that the average annual energy efficiency of monocrystalline cells was 8.3%, 8.0% and 7.1% at 9:00, 12:00 and 15:00 time zones, respectively, while amorphous cells were 2.1%, 2.2% and 2.2%. They found that the exergy efficiency of monocrystalline cells were 6.8%, 4.9% and 5.0% for 9:00, 12:00 and 15:00 h intervals, respectively, while amorphous cells were 1.3%, 0.9% and 0.7%.

3 Objective of the research

When the studies in the literature are examined, thermodynamic evaluations are made for a small period of time. In this study, energy, exergy, sustainability and exergoeconomic analyzes were carried out with the data obtained from the solar power plant located under the climatic conditions of Karapınar district for 6 months. The 6-month average values of energy efficiency, maximum electricity efficiency, power conversion efficiency, exergy efficiency, sustainability index, thermoeconomic and exergoeconomic analysis parameters of this power plant were determined. In addition, in this study, a solar power plant consisting of grid-connected photovoltaic modules with both bifacial and single axis solar tracking system is investigated by thermodynamic analysis.

4 Material and methods

4.1 Information about the solar power plant analyzed in this study

Konya Karapınar, YEKA-1 SPP, Phase-1 solar power plant is located between 37°45 and 37°47 north latitude and 33°33 and 33°35 east longitude. The total installed DC and AC powers of the plant are 267.2 MWp and

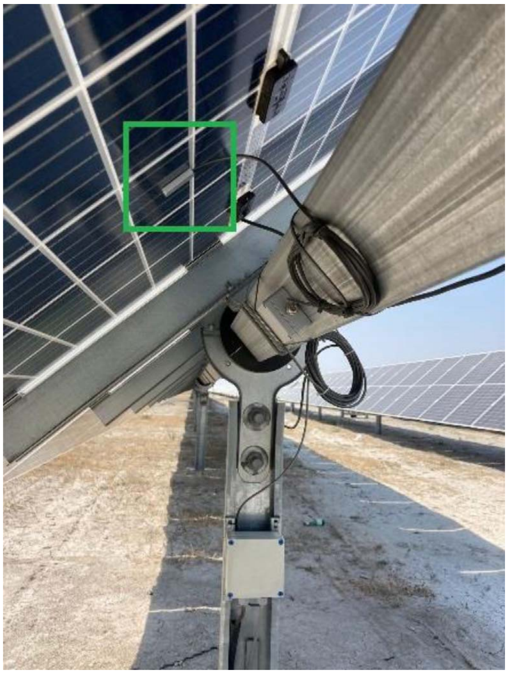


Fig. 2. An overview of PV module temperature sensor.

226.4 MWe, respectively. The total surface area of the solar panels in this power plant is 1,372,432,932 m^2. In addition, the investment cost of this power plant is approximately $200,000,000. The satellite view of the phase-1 section of the solar power plant is given in Figure 1.

The solar panels used in Karapınar YEKA-1 SPP, coded G1-144 CAM-CAM, each with a front surface of 400 Wp output power, are bifacial, monocrystalline and produced with half-cut technology. The electrical and mechanical properties of the solar panel used in the solar power plant are given in Table 1.

The technical specifications of the LV5+ 1566 Solar Inverter coded central inverters with a maximum output power of 3.43 MWe used in the solar power plant are shown in Table 2.

The global solar radiation falling on the horizontal surface is measured with the pyranometer device with the brand and product code respectively Kıpp&zonen, SMP 10-A. Temperature and wind speed are measured with the smart weather station with brand, model and product code respectively Lufft, WS-600, UMB. The temperature of the PV modules is measured with the module temperature sensor with the brand, model and product code Ingenıeurbüro, Tm-RS485-MB. For albedo measurement, 2 pyranometers of the above mentioned brand were used.

Table 1. Electrical and mechanical specifications of solar panel.

Working point voltage (V)	41.0
Working point current (A)	9.76
Maximum power (W)	400
Short circuit current (I_{sc}) (A)	10.24
Open circuit voltage (V_{oc}) (V)	48.80
Cell type	Mono-C Silicon Bifacial PERC
Cell number	144 pcs, Half cut
Module length	2024 mm ± 2 mm
Module width	1004 mm ± 2 mm
Temperature coefficient of V_{oc} (T_{ec}) (°C)	−0.28%/°C
Fill factor (FF)	0.80078125

Table 2. Technical specifications of central inverter.

Input data	
MPPT range (V_{dc})	936–1300
MPPT permissible DC Voltage (V_{dc})	1500
Maximum continuous DC current (at 35 °C/50 °C) (A_{dc})	4000/3200
Number of MPPT	1
Number of DC inputs	Up to 24
Output data	
Active AC output power (at 35 °C/50 °C) (PF = 1)[3] (MW)	3.43/3.04
AC output voltage (±%10)[4] (V_{ac})	660
Maximum AC current (at 35 °C/50 °C) (A_{ac})	3000/2655
Grid frequency (± %5) (Hz)	50/60
Inverter efficiency (Max/EU/CEC)[5] (%)	98.9/98.6/98.7

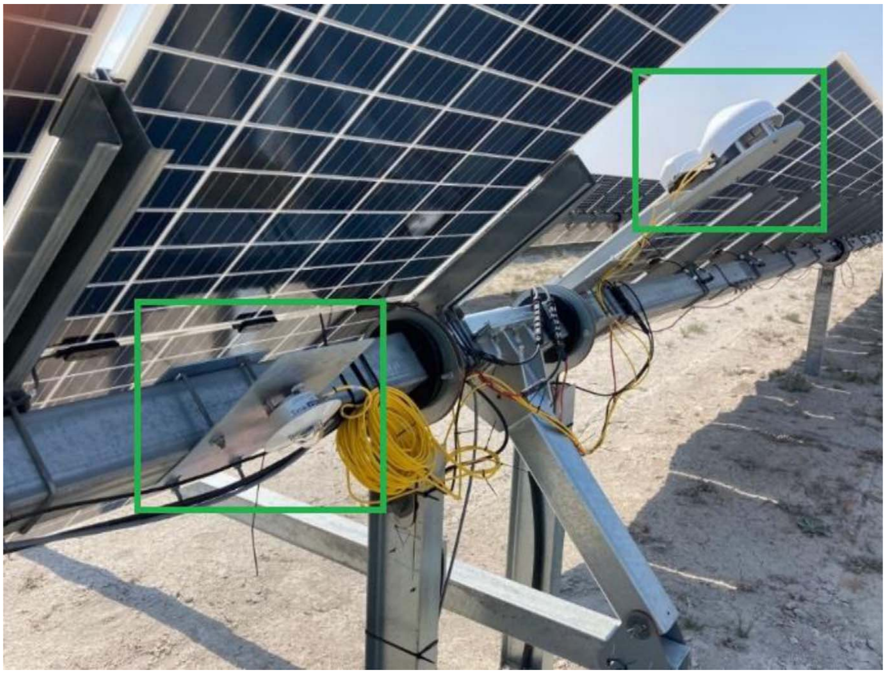


Fig. 3. An overview of albedometer.

Fig. 4. An overview of DustIQ.

One of the pyranometers is mounted facing upwards towards the sky and the other one is mounted facing downwards towards the earth. Thus, the ratio of the measurement results of the pyranometer devices to each other gives the albedo coefficient. For the cleanliness measurements of the PV modules, 2 DustIQ devices of Kıpp&Zonen brand were used. Figure 2 shows the PV module temperature sensor, Figure 3 shows the Albedometer, Figure 4 shows the DustIQ and Figure 5 shows the general views of the WMS device installations inside the power plant. Pyranometer, WS-600 UMB, PV module temperature sensor, albedometer and DustIQ measurement devices are connected to data loggers in the air monitoring stations located inside the power plant. These devices transfer the measurement data every minute to the air monitoring station via communication cables (RS 485 etc.) and then these data are transferred to the SCADA system located in the 154 KV substation of the power plant via communication cables (fiber optic cable) that can transmit over longer distances.

Figure 6 shows a schematic representation of the phase-1 section of the solar power plant.

4.2 Energy and exergy analyses

Energy analysis can be expressed as the ratio of the amount of energy at the system output to the amount of energy input based on the first law of thermodynamics. Exergy analysis helps to find the fraction of available energy that is converted into actual work using the second law of thermodynamics. The most decisive difference between exergy analysis and energy analysis is that in exergy analysis the conditions of the environment in which the system interacts are included, while in energy analysis the environmental conditions are not included.

The energy efficiency of a PV system is defined as the ratio of the output energy obtained from the photovoltaic surface to the input energy [18]. In equation (1), the energy efficiency formula is written. Where $\dot{E}_{n^{\text{output}}}$ is the output energy of the PV system, $\dot{E}_{\text{input}}$ is the input energy, $\dot{Q}$ is the thermal energy, V_{oc} is the open circuit voltage, I_{sc} is the short circuit current, S_{T} is the total solar radiation, A

is the surface area, $P_{\max}$ is the maximum output power and FF is the fill factor [3, 18].

$$\eta_{\text{en}} = \frac{\dot{E}_{n^{\text{output}}}}{\dot{E}_{n^{\text{input}}}} = \frac{V_{\text{oc}} I_{\text{sc}} + \dot{Q}}{S_{\text{T}} A} = \frac{\frac{P_{\max}}{\text{FF}} + \dot{Q}}{S_{\text{T}} A}. \quad (1)$$

Thermal energy is calculated from equation (2). Where, h_{ca} is the convection and radiation heat transfer coefficient between the solar cell and the atmosphere, T_{cell} is the PV module cell temperature and T_{amb} is the ambient temperature [19].

$$\dot{Q} = h_{\text{ca}} A (T_{\text{cell}} - T_{\text{amb}}). \quad (2)$$

The convection and radiation heat transfer coefficient between the solar cell and the atmosphere is calculated from the following equation depending on the wind speed v [19].

$$h_{\text{ca}} = 5.7 + 3.8(v). \quad (3)$$

The filling factor is calculated using equation (4) to calculate the filling factor. Where, V'_{oc} is the open circuit voltage and I'_{sc} is the short circuit current which can vary according to atmospheric conditions [19].

$$\text{FF} = \frac{P_{\max}}{V'_{\text{oc}} I'_{\text{sc}}}. \quad (4)$$

The open circuit voltage and short circuit current, which can vary according to atmospheric conditions, can be measured by measuring devices, as well as by equations (5) and (6) can be calculated with the formulas in equations (5) and (6). Here, T_{ec} is the temperature dependent voltage coefficient of variation of the solar panel under standard test conditions.

$$V'_{\text{oc}} = V_{\text{oc}} \frac{(100 + ((T_{\text{cell}} - 25)(T_{\text{ec}}))}{100}, \quad (5)$$

$$I'_{\text{sc}} = I_{\text{sc}} \left(\frac{S_{\text{T}}}{1000} \right). \quad (6)$$

The maximum electrical efficiency ($\eta_{\max,\text{el}}$) is the ratio of the maximum electrical energy produced from PV solar panels to the total input energy and is calculated from the following equation [3, 18].

$$\eta_{\max,\text{el}} = \frac{V_{\text{oc}} I_{\text{sc}}}{S_{\text{T}} A} = \frac{\frac{P_{\max}}{\text{FF}}}{S_{\text{T}} A}. \quad (7)$$

The power conversion efficiency (η_{pce}) of a PV solar panel is defined as the ratio of the maximum actual output power to the input power. It is determined using equation (8) [3, 18].

$$\eta_{\text{pce}} = \frac{P_{\max}}{S_{\text{T}} A}. \quad (8)$$

Exergy efficiency is defined as the ratio of exergy out to exergy in equation (9) gives the exergy efficiency formula. Here, $\dot{E}\text{x}_{\text{output}}$ is the output exergy, $\dot{E}\text{x}_{\text{input}}$ is the input exergy, $\dot{E}\text{x}_{\text{PV}}$ is the PV system exergy per unit time and $\dot{E}\text{x}_{\text{solar}}$ is the solar exergy [18].

$$\Psi = \frac{\dot{E}_{x^{\text{output}}}}{\dot{E}_{x^{\text{input}}}} = \frac{\dot{E}_{x^{\text{PV}}}}{\dot{E}_{x^{\text{solar}}}}. \quad (9)$$

The exergy equation of a PV system per unit time is given below [3].

$$\dot{E}_{x^{\text{PV}}} = V_{\max} I_{\max} - h_{\text{ca}} A (T_{\text{cell}} - T_{\text{amb}}) \left(1 - \frac{T_{\text{amb}}}{T_{\text{cell}}} \right). \quad (10)$$

The expression for the Jeter Solar exergy model is given in equation (11). Jeter solar exergy model is the most preferred model for calculating solar exergy [20]. In this study, T_{sun} solar temperature is taken as 5777 K [21].

$$\dot{E}_{x^{\text{solar}}} = \left[1 - \left(\frac{T_{\text{amb}}}{T_{\text{sun}}} \right) \right] (S_{\text{T}} A). \quad (11)$$

Equations (10) and (11) are substituted in equation (9), the expression for the exergy efficiency of a PV system is expressed as follows [3, 18].

$$\Psi = \frac{V_{\max} I_{\max} - h_{\text{ca}} A (T_{\text{cell}} - T_{\text{amb}}) \left(1 - \frac{T_{\text{amb}}}{T_{\text{cell}}} \right)}{\left[1 - \left(\frac{T_{\text{amb}}}{T_{\text{sun}}} \right) \right] (S_{\text{T}} A)}. \quad (12)$$

4.3 Sustainability analysis

For sustainable development, it is not only sufficient to use clean energy resources, but also to ensure that these resources are used more efficiently. Exergy efficiency is an effective method for using energy resources more efficiently, increasing efficiency and minimizing parameters that negatively affect efficiency such as irreversibility. Therefore, exergy efficiency can be used to improve the efficiency and sustainability of the system [22]. The sustainability index is determined from the following equation [23].

$$\text{SI} = \frac{1}{1 - \Psi}. \quad (13)$$

4.4 Exergoeconomic analysis

Exergoeconomic analysis defines the real product cost of a system by using economics and energy and exergy analysis together. Therefore, an exergoeconomic analysis can only be performed after the completion of energy and exergy analyses [18]. In this thesis, EXCEM (Exergy-Cost-Energy-Mass) method will be applied as an economic analysis method. Figure 7 shows the basic schematic of the EXCEM method [24]. The cost of loss rates ($\dot{R}$) is expressed in equation (14). Here, L is the thermodynamic loss and K is the investment cost [25].

$$\dot{R} = \frac{\dot{L}}{K}. \quad (14)$$

Equation (15) calculates the thermoeconomic analysis parameter ($\dot{R}_{\text{en}}$) and equation (16), the exergoeconomic analysis parameter ($\dot{R}_{\text{ex}}$) is calculated [26]. This method

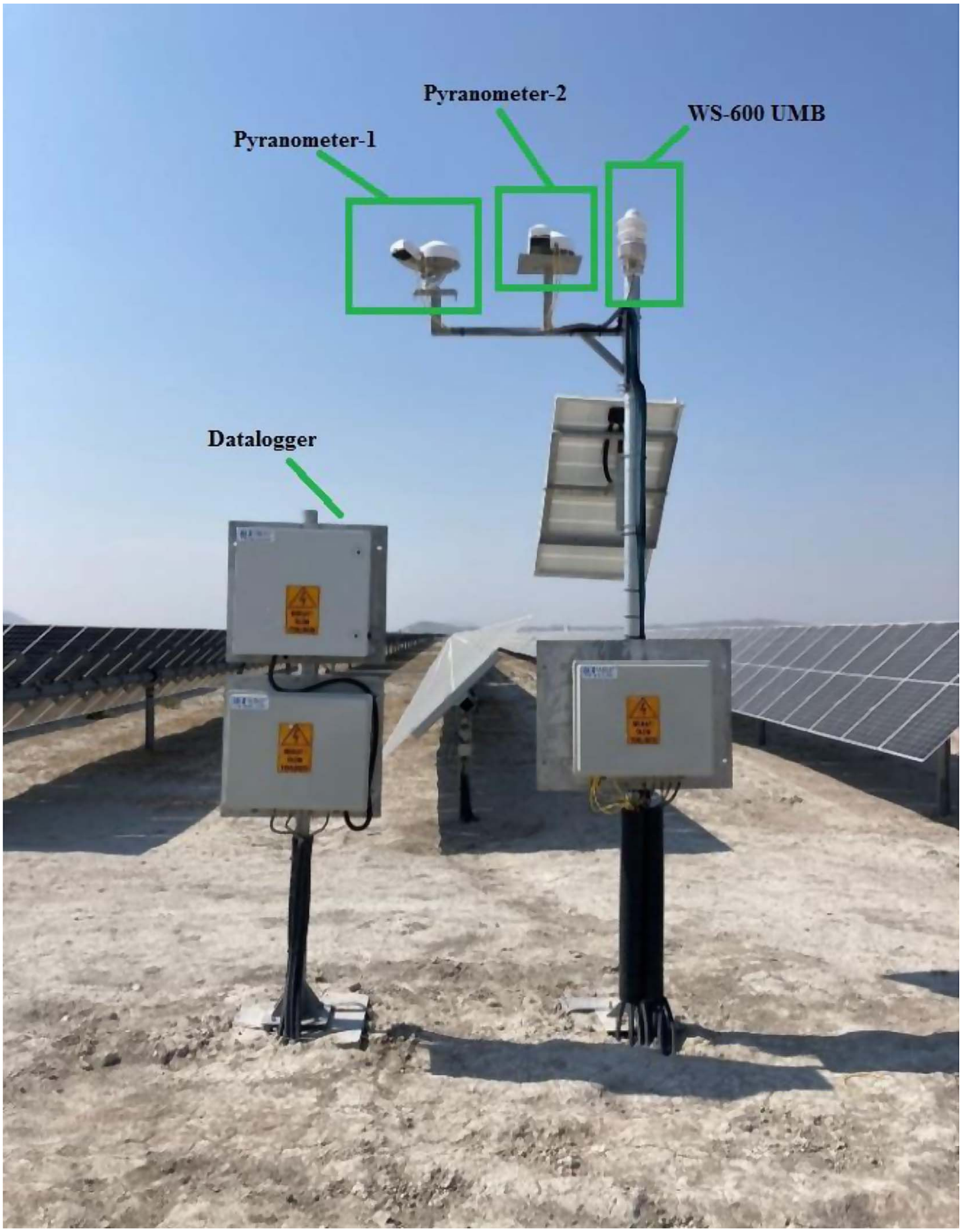


Fig. 5. An overview of weather monitoring station (WMS).

shows the amount of energy lost and exergy lost for the unit cost of installing the existing system. Here, $\dot{L}_{\text{en}}$ is the energy loss rate and $\dot{L}_{\text{ex}}$ is the exergy loss rate [25].

$$\dot{R}_{\text{en}} = \frac{\dot{L}_{\text{en}}}{K}, \tag{15}$$

$$\dot{R}_{\text{ex}} = \frac{\dot{L}_{\text{ex}}}{K}. \tag{16}$$

If analyzed in terms of energy with the EXCEM method, the difference between the energy value of the incoming solar radiation and the generated energy value gives the energy loss rate as seen in equation (17).

$$\dot{L}_{\text{en}} = \dot{E}_{n^{\text{input}}} - P_{\max} = S_{\text{T}}A - P_{\max}. \tag{17}$$

As seen in equation (18), the difference between the exergy value of the incoming solar radiation and the exergy value leaving the system gives the exergy loss rate.

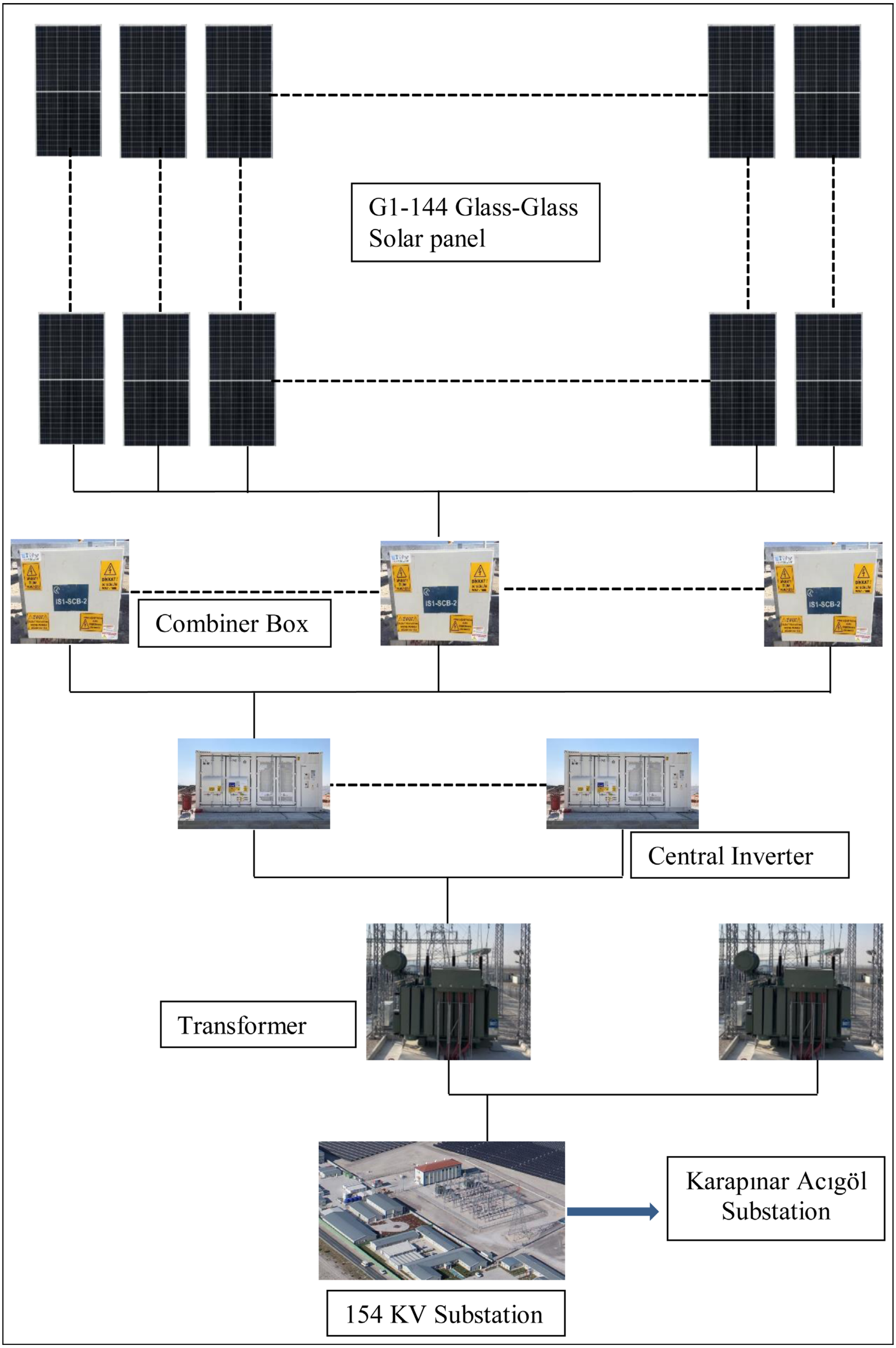


Fig. 6. Schematic representation of YEKA-1 SPP Phase-1 solar power plant Karapınar, Konya, Türkiye.

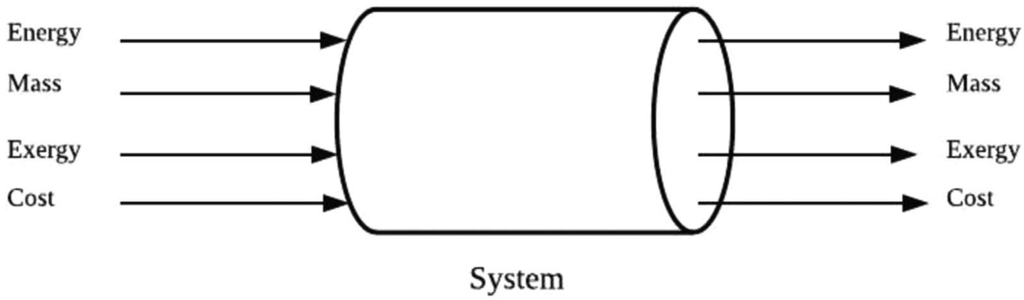


Fig. 7. Basic diagram of EXCEM method.

Table 3. Monthly average values of 6-month power plant data.

Hours (09.00–17.00)	Average maximum power output P_{max}, (MW)	Average solar radiation ST, (W/m^2)	Average wind velocity V, (m/s)	Average cell temperature T_{cell}, (K)	Average ambient temperature T_{amb}, (K)
August 2021	201.75	737.39	4.23	315.57	300.90
September 2021	187.94	623.55	3.31	309.33	294.47
October 2021	171.11	513.90	2.50	303.95	289.56
November 2021	113.19	326.11	3.22	294.40	285.08
December 2021	82.67	234.29	2.55	284.63	278.41
January 2022	75.27	292.35	3.16	280.50	272.92

Table 4. Monthly average albedo coefficient and PV module cleaning rate (6 months).

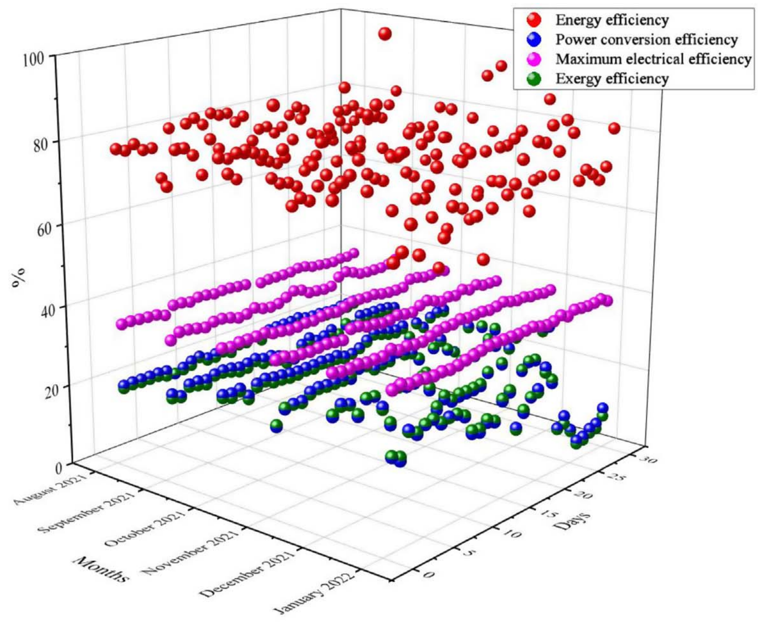
Property	August 2021	September 2021	October 2021	November 2021	December 2021	January 2022
Average Albedo coefficient	0.1145	0.1382	0.141	0.1443	0.1303	0.2349
Average cleaning ratio (%)	97.8285	98.2376	97.8697	97.5584	96.7141	90.317

$$\dot{L}_{\text{ex}} = \dot{E}_{x^{\text{input}}} - \dot{E}_{x^{\text{output}}} = \left(\left(1-\left(\frac{T_{\text{amb}}}{T_{\text{sun}}}\right)\right)(S_{\text{T}}A)\right) - \left(\left(P_{\text{max}} - (h_{\text{ca}}A)(T_{\text{cell}} - T_{\text{amb}})\left(1 - \frac{T_{\text{amb}}}{T_{\text{cell}}}\right)\right)\right). \tag{18}$$

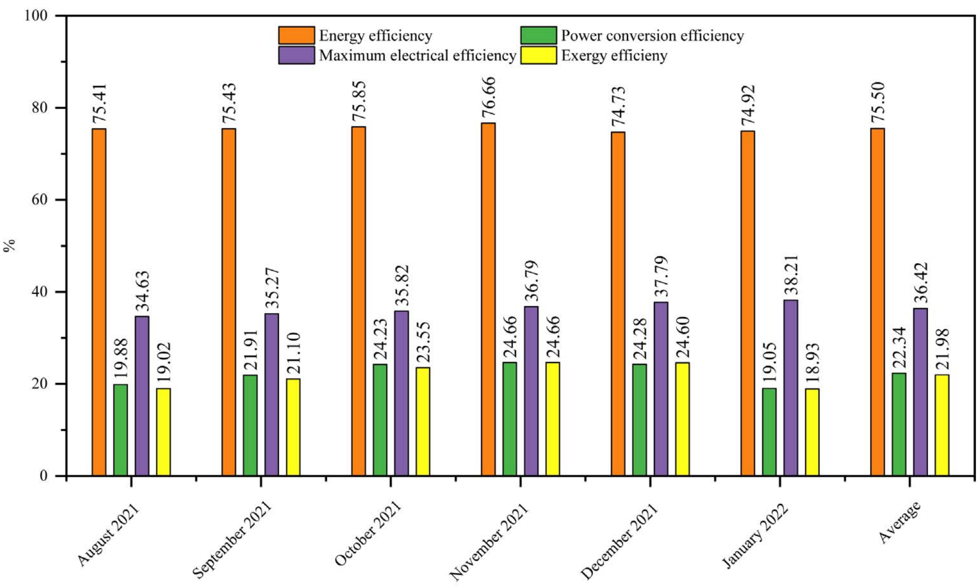
5 Results and discussion

In this study, the power plant data between 09.00 and 17.00 h during the months of August, September, October, November, December in 2021 and all days of January in 2022 were analyzed. Monthly average values at this power plant were calculated. Maximum output power generation, solar irradiance, wind speed, PV cell temperature and ambient temperature data for the six months were used for thermodynamic analysis. Table 3 shows the monthly averages of the data obtained from the power plant for 6 months. Table 4 shows the monthly average values of albedo and PV module cleaning rates for 6 months. As a result of the 6-month data obtained from the power plant, the average albedo coefficient was calculated as 0.15 and the average cleaning rate of the photovoltaic modules was calculated as 96.42%. In addition, snowfalls that occurred on some days in January increased the average albedo coefficient in January, but decreased the average panel cleaning rate in January as the panel surfaces were covered with snow.

Figure 8 shows the time variation of the average values of energy, maximum electricity, power conversion and exergy efficiencies of the solar power plant for 6 months. As can be observed in this graph, the energy and maximum electricity efficiency figures varied between 74.73%–76.66% and 34.63%–38.21%, respectively. In this sense, an increase in power conversion and exergy efficiencies was followed from August to January. The main reason for this is Manjunath *et al.* [16] showed that the ambient temperature decreases. The reason for the unexpected decrease in power conversion and exergy efficiency in January is the unfavorable weather conditions (snow, etc.) covering the panel surface. However, the high performance ratio and high system



(a)



(b)

Fig. 8. (a) Energy, maximum electricity, power conversion and exergy efficiencies and (b) monthly and overall average data.

efficiency of the PV system in winter are due to low module temperature and sufficient solar radiation [14]. Solar panels work more efficiently in cold environments with high solar radiation intensity. With 6-month data, the average energy, maximum electricity, power conversion, and exergy efficiencies of the solar power plant in Konya province were found to be 75.50%, 36.42%, 22.34%, and 21.98%, respectively. Kandilli [27] determined the exergy efficiency of monofacial PV systems as approximately 12%. Bayat and Özalp [12] found that the energy, maximum electricity, power conversion and exergy efficiencies of the system consisting of monofacial solar panels in Karabük province ranged between 24% and 68.4%, 12.6% and 23.12%, 9.6% and 18.3%, 9.3% and 18.1%, respectively. In addition, Barbosa de Melo *et al.* [28], in a study conducted in Brazil, found that the total gain of bifacial panels used in combination with solar tracking system varied between 19.39% and 27.39% compared to other systems. In another study, Palaez *et al.* [29] showed that bifacial solar panels used with single-axis solar tracking systems increase energy efficiency between 4% and 15% depending on the module type and the albedo coefficient of the location.

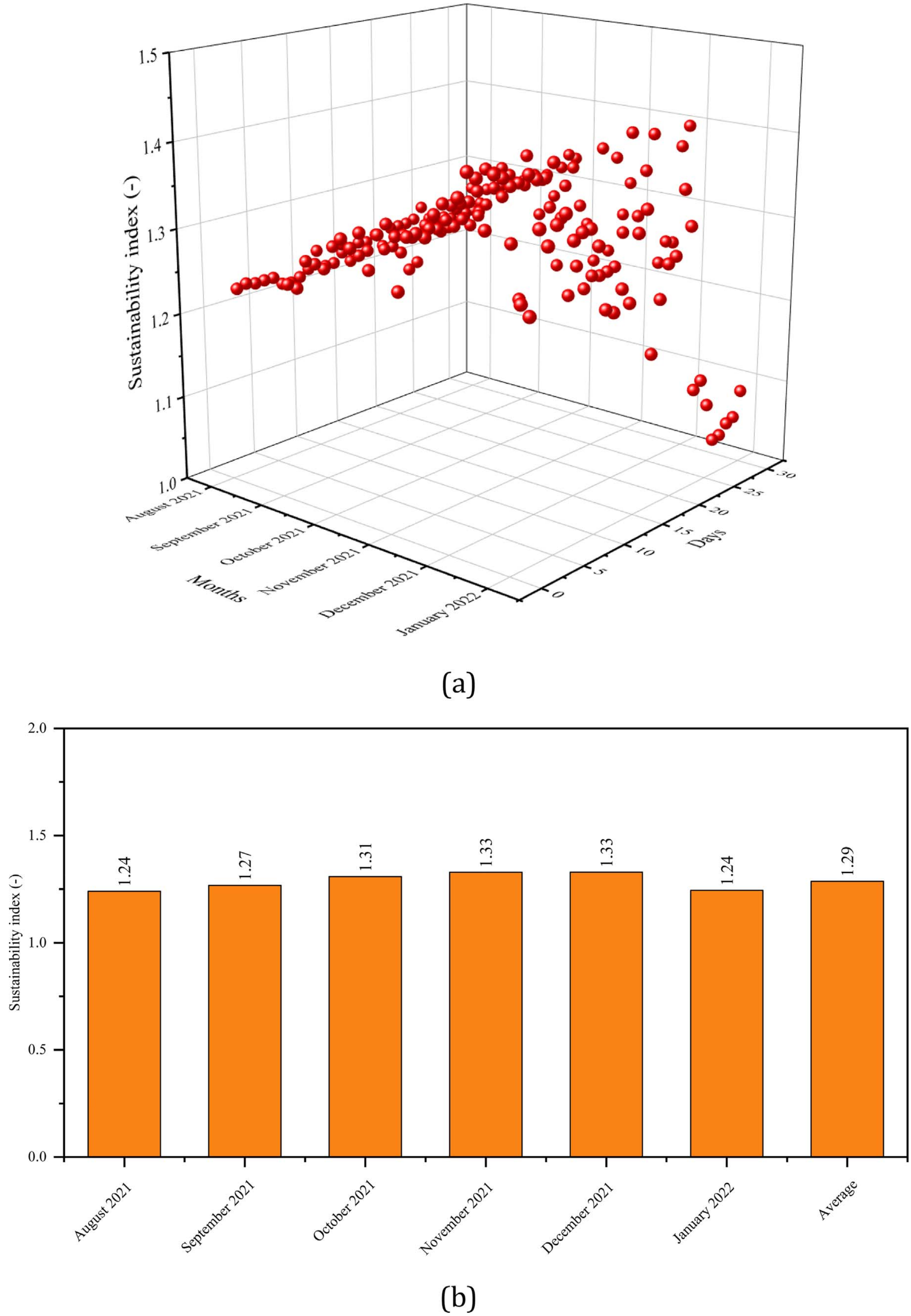


Fig. 9. (a) Sustainability index and (b) monthly and overall average data.

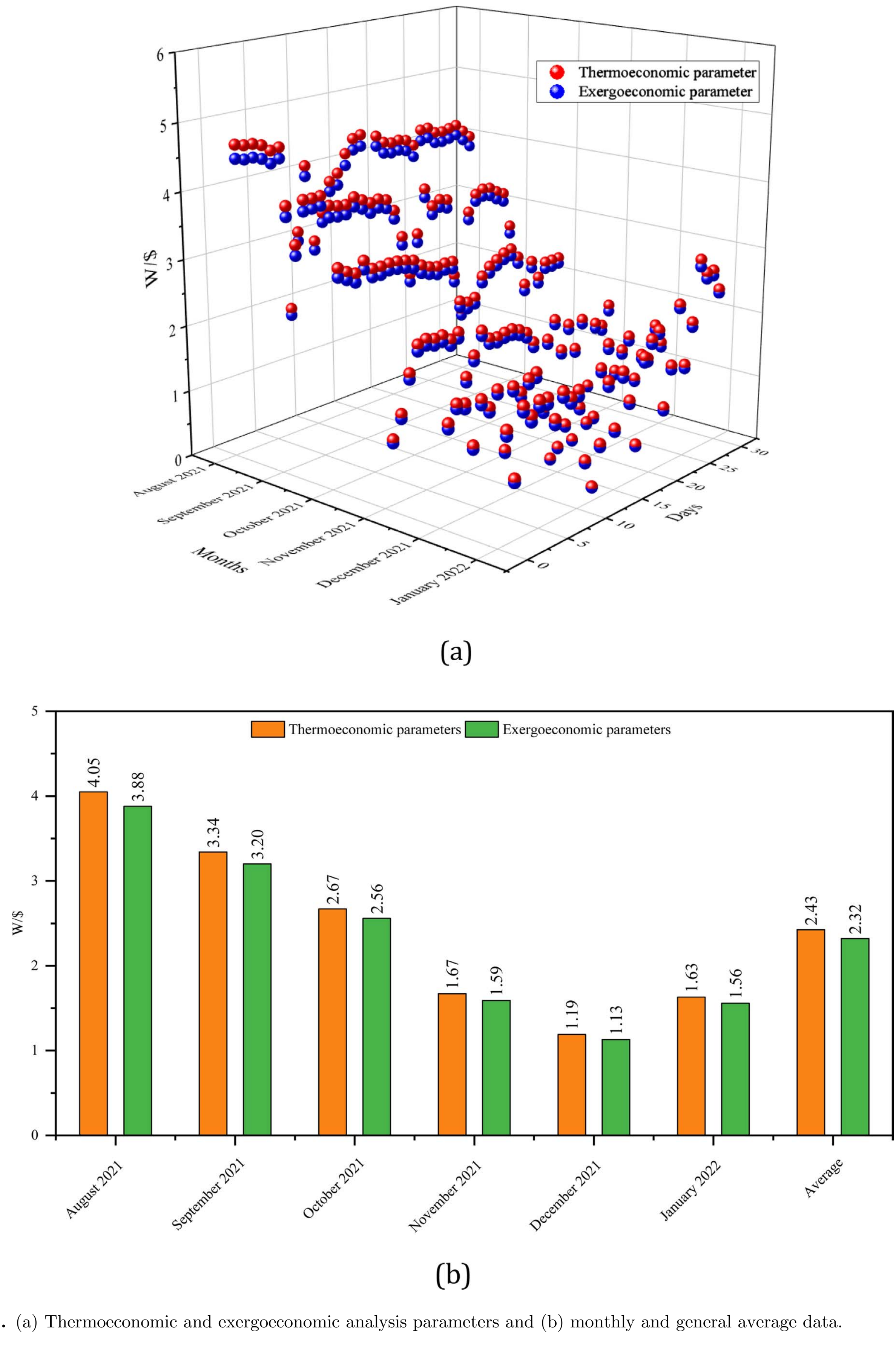


Fig. 10. (a) Thermoeconomic and exergoeconomic analysis parameters and (b) monthly and general average data.

The change in the sustainability index averages of the solar power plant over time for 6 months is given in Figure 9. As seen in this figure, the average value of the sustainability index of the solar power plant with 6-month data is calculated as 1.29. As the sustainability index rises above 1, sustainability increases. It was determined that the sustainability indices increased as we move from August to January. However, due to the unfavorable weather conditions in January, the exergy efficiency of the solar power plant was negatively affected, so the sustainability index value in January was lower than the other months.

Figure 10 shows the variation of the average thermoeconomic and exergoeconomic analysis parameters of the solar power plant over time for 6 months. The average thermoeconomic analysis and exergoeconomic analysis parameter values obtained from the 6-month data of the power plant are 2.43 W/$ and 2.32 W/$, respectively. In addition, when Figures 8 and 10 are analyzed together, it is determined that as the power conversion and exergy efficiencies increase, the thermoeconomic and exergoeconomic analysis parameters decrease. İzgi and Akkaya [30] found the thermoeconomic analysis parameter values of a 750 Wp PV system built in Istanbul as 0.222 W/$ and 0.134 W/$ in August and April, respectively, according to EXCEM model. They calculated the exergoeconomic analysis parameter values of the same system as 0.214 W/$ and 0.129 W/$ for August and April, respectively. Bayat and Ozalp [12] found that the thermoeconomic analysis parameter of the system varied between 0.06 W/$ and 0.45 W/$ and the exergoeconomic analysis parameter varied between 0.05 W/$ and 0.43 W/$ as a result of the exergoeconomic analysis they performed on a solar energy system.

6 Conclusions

In this study, thermodynamic analyses were carried out for 6 months in a grid-connected solar power plant with a power capacity of 267.2 MWp with a single axis solar tracking system consisting of monocrystalline and bifacial solar panels produced with half-cut technology. As a result of these analyzes, the following evaluations were made.

- In the calculations made in line with the data obtained as a result of the experimental studies; energy efficiency, maximum electricity efficiency, power conversion efficiency, and exergy efficiency of the solar power plant were found to be 75.50%, 36.42%, 22.34%, and 21.98%, respectively.
- The sustainability index of the power plant was determined as 1.29.
- Thermoeconomic and exergoeconomic parameter values of the solar power plant within the scope of exergoeconomic analysis were calculated in W/$. The thermoeconomic and exergoeconomic parameter values of the power plant were found to be 2.43 W/$ and 2.32 W/$, respectively.
- Environmental conditions are taken into consideration in exergy analysis. Exergy efficiency has the smallest value among all efficiencies. Therefore, it would be a more realistic approach to consider the exergy efficiency while performing efficiency and feasibility studies during the installation phase of solar power plant systems.
- Solar power plants operate more efficiently in cold environments with high solar radiation intensity. However, adverse weather conditions (snow, rain, etc.) reduce efficiency.

In future studies, thermodynamic analyses of biaxial solar tracking systems consisting of bifacial PV modules can be taken into consideration. Materials with high Albedo coefficients can be laid on the ground surface and their utilization in the photovoltaic systems can be investigated in detail. Besides that, studies on power conversion and exergy efficiencies of the photovoltaic system can be accomplished by using dual-axis solar tracking systems.

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Conflict of interest

The authors pointed out that there is no potential conflict of interest.

Data availability

The data used and/or analyzed throughout the present study are available from the authors on reasonable request.

Ethical approval

The authors declared that no animal and human studies are presented in this manuscript and no potentially identifiable human images or data are given in this research.

Competing interests

The authors declared that there is no competing financial interest in this research.

Authorship contribution

Miraç Can OZTURK: Investigation, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Battal DOGAN: Conceptualization, Investigation, Methodology, Data curation, Validation, Resources, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Murat Kadir YESILYURT: Methodology, Data curation, Validation, Visualization, Writing – original draft, Writing – review & editing.

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