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Research Note

Analysis of exergy efficiency for a grid connected PV power plant via different solar exergy models in Samsun, Turkey

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Abstract. This study investigates power conversion efficiency and exergy of a grid-connected photovoltaic (PV) power plant by comparing solar exergy models at a time interval of 12 months. Statistical analysis was carried out to evaluate the PV exergy efficiency related to solar exergy models. First, solar exergy models proposed by Petela, Spanner, and Parrott and the mean of solar exergy-to-solar radiation energy ratio were calculated, and the PV exergy efficiency was analyzed. The results indicate that the average solar exergy-to-solar radiation energy ratio for the Samsun region was 0.93 related to Petela and Spanner's model. The ratio for Parrott's model was calculated as 0.99. The results confirm that the power conversion efficiency is in the range of 6.15–8.87%. While the PV exergy efficiency related to Parrott's model is seen to vary between 4.85% and 7.09% during 12 months, it changes from 5.19% to 7.60% in Petela and Spanner's model.

1. Introduction

Solar panel technology is one of the fast-developing devices for collecting solar irradiation, which is unlimited and free for all people in the world [1,2].

The thermodynamic analysis of a closed system is differently carried out based on quantization theory, exergy, or available energy; in other words, exergy is the one that can be described theoretically in terms of usable maximum work of a thermodynamic system [3]. Dincer discussed the relationship among energy transformation, exergy, and sustainable development from a scientific point of view [4]. The exergy efficiency of a system was considered to analyze the performance with respect to the corresponding performance in reversible conditions or the system's effectiveness in practical working circumstances [5]. An evaluation method was recommended to ensure that the policies of sustainable development as well as economic and environmental impacts of renewable energy systems form the optimization and performance analysis of the design of solar PV systems [5–11]. Thus, the exergy efficiency was achieved by precise engineering and scientific installation designs by taking into account different environmental parameters of regions [12].

It is known that the performance of PV panel is negatively affected by many environmental parameters such as partial or full shading, dust, paint, reflection, etc. [2]. In other words, these parameters will adversely affect the PV exergy and exergy efficiency significantly.

Generally, the exergy efficiency analysis of PV

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systems is discussed in two basic steps: the solar exergy of the area where the PV plant is designed and the exergy efficiency of the PV system related to it.

The optimization of the design of solar devices, such as solar energy collectors and PV systems, and the evaluation of their performance require accurate and realistic data about the solar energy potential in that region. In practice, solar radiation exergy includes qualitative and quantitative data of regional solar radiation, which will give maximum possible output that can be produced while considering the properties of the regional solar radiation [13–15]. It is known that the upper limit of solar energy conversion can be determined by taking into account the environmental factors affecting the solar radiation that will be received in the areas where the PV system will be installed. This upper limit of conversion is also known as the exergy of solar radiation.

Solar radiation exergy essential for efficiency evaluation of solar-powered power systems was theoretically investigated in chronological order by the following studies: Petela [16], Spanner [17], Parrott [18], Jeter [19], Bejan [20], Alta et al. [21], Hepbasli and Alsuhaibani [22], Jamil and Bellos [23], Korasanizadeh and Sepehrnia [24], etc.

Petela [16] formulated the available energy called exergy with the determining parameters, namely the surface temperature of the area where the sunbeams hit the earth and the temperature of the sun's surface. In the same year that Petela presented an article paper, Spanner [17] suggested that the exergy of solar radiation would be equal to the work potential of the system. Parrott [18] developed the suggested solar exergy model of Petela by adding the geometry of the sun-earth axis motion of the incoming sun radiation, that is, the half-angle of the cone formed. Jeter [19], on the other hand, applied Spanner's work model with a different point of view, namely the Carnot heat engine model, to solar radiation exergy. Bejan [20] examined Petela, Spanner, and Jeter's theories and concluded that they were individually correct. All the three theories were the result of a high-temperature isotropic radiation source that had a heat input from a high-temperature heat reservoir. Alta et al. [21] mapped the monthly average solar radiation exergy using the solar radiation data of 152 meteorological stations in different geographical locations in Turkey. In this study, the mean exergy value of solar radiation was at 13.5 ± 1.74 $\mathrm{MJm^{-2}day^{-1}}$, with a mean annual exergy-to-energy ratio of 0.93. Hepbasli and Alsuhaibani [22] studied the solar exergy models proposed by Petela, Spanner, and Jeter in solar energy-related applications and determined the solar exergetic values for some regions of Saudi Arabia and Turkey. The values found are close to each other. Jamil and Bellos [23] developed empirical models of the solar radiation exergy potential in different cities of India. In this study, the exergy data of direct and diffuse solar radiation were calculated and they were correlated to obtain the exergy of the global exergy efficiency factor. Beam and diffuse exergy efficiencies were in the range of 0.9286 and 0.9365 and 0.7189 and 0.7499, respectively. Korasanizadeh and Sepehrnia [24] studied solar exergy potential with five experimental models: linear, quadratic, cubic, exponential, and power functional forms that depend only on relative sunlight duration, using solar, and metrological data of eight cities in Iran. The results show that the ratio of exergy to energy can be considered as 0.87 for the entire country.

As seen from the studies of the reviewed literature, they concluded that the results of all theories such as Petela [16], Spanner [17], and Jeter [19] were close to each other and they can be considered to be correct. Besides, most of the engineering calculations of the exergy efficiency of thermodynamic systems have been based on the solar exergy models of Petela and Spanner.

The energy and exergy analysis (thermodynamic analysis) of PV and PVT systems has been performed by many researchers including Sahin et al. [25], Akyuz et al. [26], Bayrak et al. [27,28] and Bayrak and Oztop [29], Sopian et al. [30], Kumar et al. [31], Kallio and Siroux [32], Kim et al. [33], Miskat and Rashedi [34], Hasan et al. [35], Manjunatha et al. [36], etc.

Şahin et al. [25] examined the thermodynamic properties of solar PV cells depending on exergy. In their study, the output exergy was calculated based on the physical and chemical components of the solar cell. The exergy efficiencies ranged from 2% to 8%. Akyüz et al. [26] proposed a new computer calculation approach to determine the maximum amount of exergy that could be taken from the sun. In their study, they used the experimental data obtained from a PV system installed in Turkey and applied it to a conventional photovoltaic system in order to formulate the exergy efficiency of the system. Bayrak et al. [27] designed an experimental setup to investigate the electrical performance and thermodynamic analysis of a 75 W photovoltaic panel at different shading ratios. The energy and exergy efficiencies for non-shading panel were found 8.19% and 8.05%, respectively. In another study of Bayrak et al. [28], energy and exergy analysis was carried out by applying different wing parameters (length, arrays) to PV panels in the climatic conditions of Elazig, Turkey. They concluded that temperature was not distributed homogeneously and the values of panel were calculated as 11.55%, and 10.91%, respectively. In addition, Bayrak and Oztop [29] investigated the effects of static and dynamic shading on the thermodynamic and electrical performance of PV panels. The results showed that the lowest and the highest efficiency values for the panel with dynamic shading were 0.86% and 10.27%, respectively. Sopian et al. [30] carried out experimental and computational studies to improve the electrical and exergy efficiency of PV/T systems under outdoor conditions in Bangi, Malaysia using two cooling techniques. As a result of their study, they reported cooling through nano liquid and nano-PCM-based nano fluid to be more efficient than conventional water-based cooling. Results showed that nanofluid with nano-PCM achieved the highest electrical exergies of 73 and 74.52, respectively. Kumar et al. [31] compared Water-based Photovoltaic (WPV) to traditional Land-based Photovoltaic (LPV) installations. They found that the exergy efficiency of SPV was 3.07% higher than the FPV and 43.65% higher than LPV installation methods. Kallio and Siroux [32] studied the energy and exergy of a PVT collector in comparison to a photovoltaic (PV) panel under two different European climate conditions. The total exergy in Strasbourg was 1.27% higher than that in Tampere. Kim et al. [33] conducted energy and exergy analyses of the inlet flow, radiation intensity, and PV module at the temperature of the air-type PVT collector with outdoor experiments. They found that the total exergy efficiency of the air-type PVT collector with perforated baffles was about 20% difference. Miskat and Rashedi [34] determined the solar exergetic map and the environmental cost of a solar PV system in Nepalese cities; city of Janakpur carries the highest amount of solar PV exergy with the efficiency of 36.27% during a year. Hasan et al. [35] investigated effects of different environmental and operational factors on the PV performance. They found dust allocation and soiling effect to be crucial, along with the humidity and temperature that largely affect the performance of PV module. Manjunatha et al. [36] analyzed energy and exergy performance of a 50 W solar photovoltaic panel. Another experimental study investigated the electrical, thermal, and exergy output of the solar PV panel.

In this study, the basic three solar exergy models of Petela, Spanner, and Parrot were analyzed theoretically and experimentally by taking measurements of a grid-connected PV power plant in real weather conditions on a clear and sunny day for 12 months of the year in the city of Samsun, Turkey. Finally, exergy efficiencies were realized by considering environmental conditions such as wind speed and solar cell temperature.

2. Materials and methods

2.1. PV array power plant

The grid-connected PV plant has a maximum capacity of 114 kW and was built on an area of 10000 m^2. The PV power plant consists of 440 poly-crystalline panels, each with maximum output of 260 W, and the electric current generated from the sun is controlled by 4 inverters of 30 kW. One array with 124 panels was used for the analysis. This PV plant was installed with the support of the European Union project. Image of the solar power plant is given in Figure 1, mounted at 41°17′ 15.00″ N and 36°20′ 0.60″ E.

Figure 1. Satellite image of the solar power plant.

2.2. Methods

The analysis of the PV array was conducted at Ondokuz Mayis Universitesi Teknopark' under weather conditions in Samsun city, Turkey. The data for this study were collected on different clear and cloudless days in the province of Samsun between June 2019 and May 2020 over a period of 12 months.

This study analyzes the parameters of solar exergy namely solar irradiation, ambient wind speed (v), outdoor air temperature (T_a), generated open-circuit voltage (V_{oc}), short-circuit current (I_{sc}) of the system, output voltage (V), and output current (I). The analyses of energy, solar exergy, and exergy of the PV plant were conducted through the following steps:

- Instantaneous output electrical power generation (P) data were obtained from the inverter;
- The total solar radiation incident on the surface of the photovoltaic (I_s) was measured with a Kipp & Zonen Pyranometer;
- Wind speed (v) was measured with Wellhise HT-380 digital anemometers;
- Ambient temperature (T_a) and cell temperature (T_{cell}) data were measured using the T-type thermocouples;
- By using the obtained data for each month, the solar exergy and PV system exergy efficiency using Petela, Spanner, and Parrott's model were analyzed;
- The obtained results from Petela, Spanner, and Parrott's model were compared in terms of solar exergy and PV exergy efficiency.

3. Theoretical analysis

The efficiency analysis for a PV power plant can be made based on the first and second laws of thermodynamics including energy, entropy, and exergy balance.

3.1. Energy analysis

The first law of thermodynamics discusses the energy analysis of the PV system. Solar irradiation (I_s) is the sun's radiant energy incident on a surface of a unit area, expressed in W/m^2. Incident solar power is given as:

$$P_{sun} = I_s \times A. \tag{1}$$

By reaching solar radiation on the surfaces of panels, PV device converts it into usable electricity.

Maximum electrical output power of the PV panel is given by:

$$P = V_m \mathrm{I}_m, \tag{2}$$

PV power conversion efficiency is the percentage of incident solar energy converted into electricity;

$$\eta_{pce} = \frac{V_m I_m}{I_s A}, \tag{3}$$

where (I_m), (V_m), and (A) represent the maximum current, the maximum voltage, and the photovoltaic panel area, respectively. In this study, the PV array surface is 201 m^2.

3.2. Exergy analysis

The exergy efficiency (ψ_{PV}) of any system can be expressed as the ratio of output exergy ($\dot{E}x_{out}$) to input exergy ($\dot{E}x_{in}$); then, for calculating exergy efficiency, input exergy and output exergy should be examined:

$$\Psi_{PV} = \frac{E\dot{x}_{out}}{E\dot{x}_{in}}. \tag{4}$$

Calculation of solar radiation exergy was mainly done and proposed by Petela, Parrott, and Spanner. According to Petela's theorem, the net input exergy of a PV panel including solar radiation intensity is given by [16]:

$$\dot{E}x_{in} = AI_s \left[\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right] + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right], \tag{5}$$

where T_s is the surface temperature of sun, which is about 5800 K.

In Spanner's model, the input exergy of a PV is calculated as work potential [17]:

$$\dot{E}x_{in} = AI_s \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right]. \tag{6}$$

Different in nature from previous studies, this study calculated the input exergy of a solar photovoltaic array by considering the geometry of the incoming radiation (Parrott's model) [17]:

$$\dot{E}x_{in} = AI_s \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)(1-\cos\sigma)^{\frac{1}{4}} + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right], \tag{7}$$

where σ is the half-angle of the cone subtended by the sun's disc. The calculated σ values have been observed to change from 0.0046 (July) to 0.0047 (January). These limit values correspond to the minimum (July) and maximum (January) distances of the earth to the sun. In this study, the approximate value of σ is obtained as 0.005 using Parrott's model (Eq. (7)) [18].

The ratio of solar radiation exergy to solar radiation energy (exergy to energy ratio) can be calculated using Petela (Eq. (8)) [16], Spanner (Eq. (9)) [17] and Parrott's model (Eq. (10)) [18] as follow:

$$\Phi_{Pet} = 1 - \frac{4}{3}(\frac{T_a}{T_s}) + \frac{1}{3}(\frac{T_a}{T_s})^4, \tag{8}$$

$$\Phi_{Span} = 1 - \frac{4}{3}(\frac{T_a}{T_s}), \tag{9}$$

$$\Phi_{Parr} = 1 - \frac{4}{3}(\frac{T_a}{T_s})(1-\cos\sigma)^{\frac{1}{4}} + \frac{1}{3}(\frac{T_a}{T_s})^4, \tag{10}$$

where Φ_{Pet}, Φ_{Span}, and Φ_{Parr} denote the ratio of solar radiation exergy to solar radiation energy related to the Petela, Spanner, and Parrott's models, respectively.

The output exergy ($\dot{E}x_{out}$) for a PV system is equal to the electrical exergy ($\dot{E}x_{electrical}$) (electrical energy produced by the system) minus thermal exergy ($\dot{E}x_{ther}$) as heat loss:

$$\dot{E}x_{out} = \dot{E}x_{electrical} + \dot{E}x_{ther}. \tag{11}$$

The electrical exergy of a PV array is given by:

$$\dot{E}x_{electrical} = I_m V_m. \tag{12}$$

The heat loss from the PV surface to the environment can be expressed as thermal exergy:

$$\dot{E}x_{ther} = \dot{Q}\left[1 - \left(\frac{T_a}{T_{cell}}\right)\right], \tag{13}$$

where:

$$\dot{Q} = h_{ca} A(T_{cell} - T_a), \tag{14}$$

and:

$$h_{ca} = 5.7 - 3.8v, \tag{15}$$

where T_{cell} is the temperature of the cell, h_{ca} the heat transfer coefficient, and v the wind velocity.

By using Eqs. (12) and (13), the output exergy can be written as follows:

$$\dot{E}x_{out} = I_m V_m - \left[1 - \left(\frac{T_a}{T_{cell}}\right)\right] h_{ca} A(T_{cell} - T_a). \tag{16}$$

By taking into account the solar exergy models (Petela, Parrot, and Spanner) which have a different amount of input exergy in Eq. (5), the exergy efficiency of a PV system is calculated separately for each model and compared.

By substituting Eq. (5) (Petela's input exergy model) and Eq. (16) into Eq. (4), the exergy ratio of the PV system using Petela's model is analyzed in the following:

$$\Psi_{PV} = \frac{I_m V_m - [1 - (\frac{T_a}{T_{cell}})] h_{ca} A (T_{cell} - T_a)}{A I_s [1 - \frac{4}{3}(\frac{T_a}{T_s}) + \frac{1}{3}(\frac{T_a}{T_s})^4]}. \quad (17)$$

In the same way, exergy efficiency of the PV system using Spanner's model (Eq. (18)) and Parrott's model (Eq. (19)) is given below:

$$\Psi_{PV} = \frac{I_m V_m - [1 - (\frac{T_a}{T_{cell}})] h_{ca} A (T_{cell} - T_a)}{A I_s [1 - \frac{4}{3}(\frac{T_a}{T_s})]}, \quad (18)$$

$$\Psi_{PV} = \frac{I_m V_m - [1 - (\frac{T_a}{T_{cell}})] h_{ca} A (T_{cell} - T_a)}{A I_s [1 - \frac{4}{3}(\frac{T_a}{T_s})(1 - \cos\sigma)^{\frac{1}{4}} + \frac{1}{3}(\frac{T_a}{T_s})^4]}. \quad (19)$$

To investigate the exergy efficiency of a PV system, i.e., the exergy of solar radiation, the widely used Petela's model (Eq. (5)) was proposed. In this study, in the case of a grid-connected PV plant in real environmental conditions, the solar radiation exergy recommended by Petela, Spanner, and Parrott was compared in the time interval of 12 months and the exergy efficiency was calculated for each solar exergy model.

4. Result and discussions

In summary, the solar exergy models proposed by Petela, Spanner, and Parrot were compared theoretically and experimentally by considering the data of a grid-connected PV power plant and environmental meteorological conditions. The environmental data, the intensity of sunlight, wind velocity (v), ambient temperature (T_a), solar cell temperature (T_{cell}), and power output (P) of a grid-connected PV power plant for 12 months a year were collected. Finally, by considering wind speed and solar cell temperature, the exergy efficiency (ψ) for each month were analyzed. The variation of solar radiation depending on the investigated solar exergy models can be seen in Figure 2.

As shown in Figure 2, the result of input solar exergy for Spanner's model is almost equal to that for Patela's model. This is because the ratio of ambient temperature to the temperature of the sun is very low and this brings about agreement between Petela's solar exergy model (Eq. (5)) and Spanner's solar exergy model (Eq. (6)). It can be seen that the solar exergy for Parrott's model is higher than that for Spanner and Petela's models in each month. The input of exergy changes from 68668 W in June 2019 to 43176 W in February 2020 in Parrott's model, while in Spanner and Petela's models, it changes from 64261 W to 40528 W in the same months. As seen from these results, the

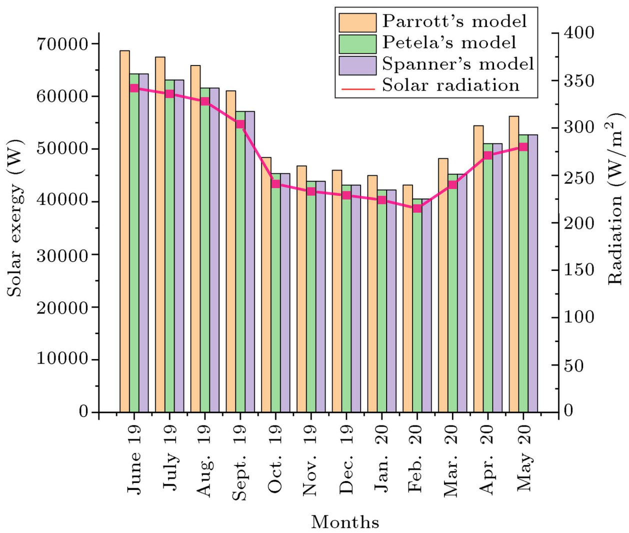

Figure 2. Effect of the solar radiation on the input exergy models for different months.

increase of solar radiation increases the solar exergy of the PV array, and the input exergy directly depends on solar radiation.

In solar exergy calculations, it is important to consider the direction of solar radiation in a fundamental way. It is also essential that the direction of the solar radiation be limited to a half-angle cone $\sigma = 0.005$ rad [18]. By considering the geometry of the incident solar radiation, Parrott presented a more realistic and near-complete model than other solar exergy models.

The average solar radiation exergy is obtained as 14.62 MJ/m^{2}day for spring, 15.08 MJ/m^{2}day for summer, 6.41 MJ/m^{2}day for autumn, and 7.67 MJ/m^{2}day for winter. The annual mean exergy value of solar radiation in the Samsun region is calculated as 10.97 MJ/m^{2}day corresponding to Petela and Spanner's models. The ratio of solar radiation exergy to solar radiation energy in the case of Petela and Spanner's approach for the Samsun region is found to be 0.93. These results are in line with the results reported by Alta et al. [21]. The ratio of solar radiation exergy to solar radiation energy related to Parrott's model reached up to 0.99. The mean solar radiation exergy in Parrott's model is approximately 6% higher than Spanner and Petela's model for each month.

Figure 3 presents variation in solar exergy and electrical exergy values of the PV array for different months. The electrical exergy is significantly less than the energy that could be extracted. These losses result from the system's irreversibility.

The ambient temperature and PV cell temperature related to the output exergy and thermal exergy for different months are shown in Figure 4.

As illustrated in Figure 4, the value of PV exergy changes from 2122.40 W in February 2020 to 4889.61 W in June 2019. That is, the increase in ambient temper-

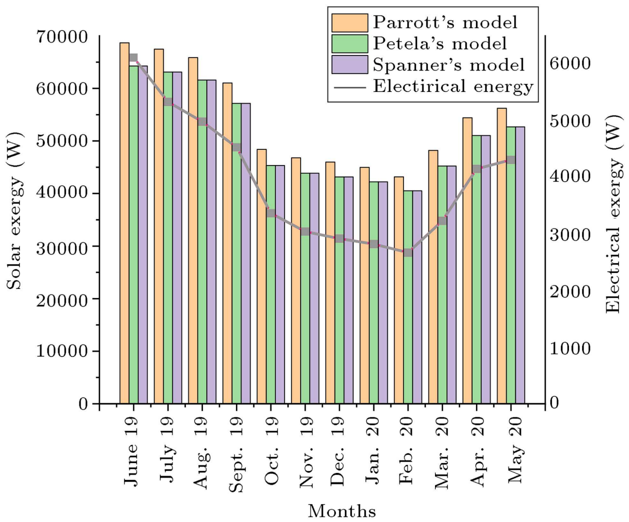

Figure 3. The electrical exergy and input exergy models for 12 months.

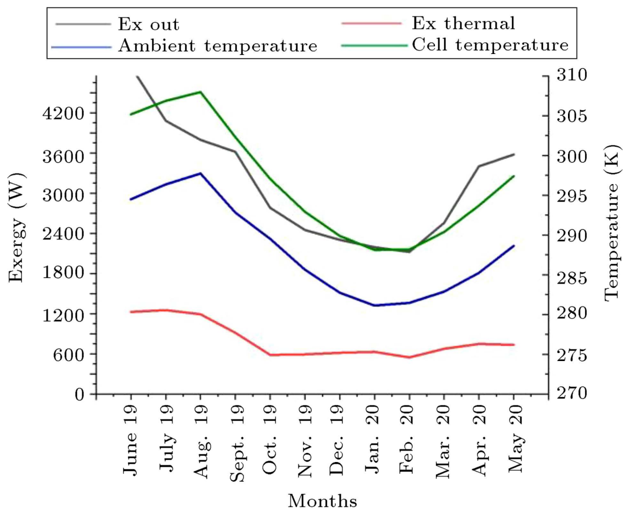

Figure 4. The effects of ambient and solar cell temperature on output exergy and thermal exergy.

ature increases cell temperature and thermal exergy of PV array and PV exergy is dependent on thermal exergy.

Wind speed is another effective parameter for analyzing the convective coefficient heat loss which is used to calculate the thermal exergy of a PV module. The average wind speeds for the installation place vary between 2.22 m/s and 3.77 m/s during a year.

The variation of power conversion and exergy efficiencies for different months are illustrated in Figure 5. The value of power conversion efficiency (η_{pce}) changes from 8.87% in June 2019 to 6.15% in February 2020 and exergy ranges from 4.87% to 7.60% for all models. From the evaluation of the result shown in Figure 5, it is clear that exergy efficiency (ψ) related to the solar exergy models is lower than the power efficiency (η_{pce}). It is seen that environmental factors of the region, where the PV power system is installed greatly, affect the output power generation, but the intensity of the radiation from the sun does not directly increase the exergy output of the system. The power conversion and exergy efficiency values of the analyzed PV power system are close to those published by Bayrak et al. [27–29].

Figure 6 shows the exergy efficiency comparison among Parrott, Spanner, and Petela's models of a grid connected PV in the different months.

As illustrated in Figure 6, the exergy efficiency for Spanner and Petela's models is higher than that for

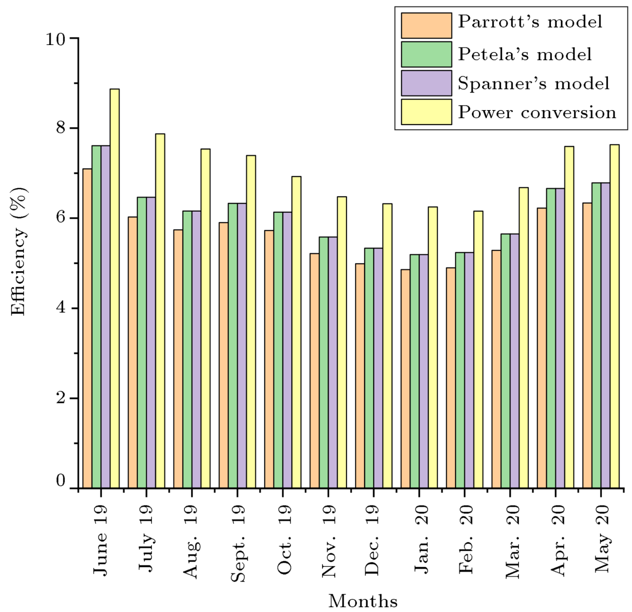

Figure 5. The variation of power conversion and exergy efficiencies related to Spanner, Petela, and Parrott's model for 12 months.

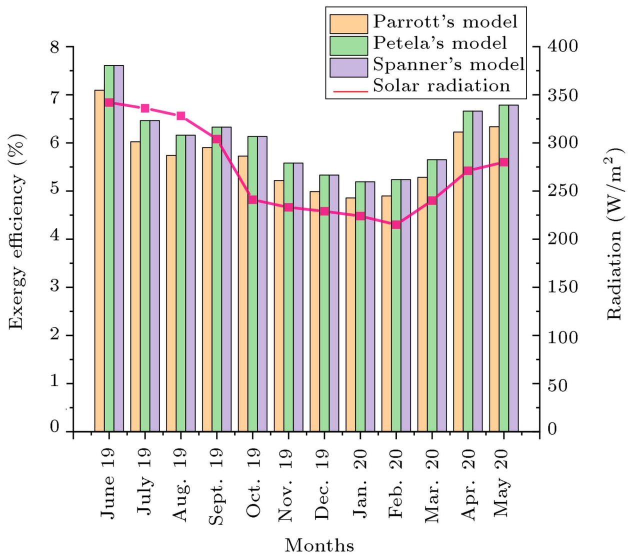

Figure 6. Exergy efficiency comparison related to Parrott, Spanner, and Petela's models for different months.

Parrott's model in each month. The exergy efficiency ranges about 7.60% in June 2019 to 5.19% in February 2020 for Spanner and Petela's models; in the case of Parrott's solar exergy model, it changes from 7.09% to 4.85% in the same months. The exergy efficiency related to the solar exergy models was calculated, where the increase ($\sim$ 6%) in input exergy for Parrott's model caused a decrease (6%) in exergy efficiency. The exergy efficiency measured using Parrot's model was approximately 6% less than that for Spanner and Petela's models in each month.

5. Conclusions

In conclusion, based on the first and second laws of thermodynamics, power conversion efficiency, solar exergy and exergy efficiency of a grid-connected photovoltaic power plant was analyzed for 12 months, and the exergy efficiency related to the solar exergy models of Parrott, Spanner, and Petela was calculated and compared. Initially, energy/exergy calculations were done by taking measurements using a single solar panel on a clear and sunny day. For the whole study, throughout 12 months of a year, data collection in the case of a grid-connected PV power plant was done in real weather conditions and the solar exergy calculations were conducted by considering the three solar exergy models. Finally, the exergy efficiencies were realized, taking into account the wind speed and solar cell temperature. This study was performed via a realistic view to the industrial and scientific community. The results are summarized below:

- The average solar exergy-to-solar radiation energy ratio for the Samsun region was found to be 0.93 related to Petela and Spanner's models. This ratio for Parrott's model reached up to 0.99;
- The average exergy value of solar radiation in the Samsun region was obtained as 10.97 MJ/m^2day related to Petela and Spanner's models. This value for Parrott's model was calculated at 11.62 MJ/m^2day for the Samsun region;
- The increase in the ambient temperature increased the PV cell temperature; in other words, PV exergy efficiency adversely affected PV cell temperature;
- Environmental factors had a notable impact on the exergy efficiency of the PV power system;
- The PV exergy efficiency using Parrott's solar exergy model varied between 4.85% and 7.09% during 12 months of the year. In Petela's and Spanner's solar exergy models, it varied from 5.19% to 7.60%;
- Exergy efficiency of the system related to Parrot's model was approximately 6% less than that for Spanner and Petela's model;
- PV exergy efficiency data could be more detailed when considering the geometry of the incident solar radiation for Parrott's solar exergy model.

Nomenclature

A	Area (m^2)
$\dot{E}x$	Exergy (W)
h_{ca}	Heat transfer coefficient
I	Current (A)
I_S	Solar radiation (W/m^2)
P	Electrical power (W)
T	Temperature (K)
V	Voltage (v)
v	Wind speed (m/s)

Greek symbols

η_{pce}	Power conversion efficiency
ψ	Exergy efficiency
σ	Angle (rad)
Φ	Solar exergy to solar energy ratio

Subscripts

a	Ambient
$cell$	Cell
m	Maximum
in	Input
out	Output
PV	Photovoltaic
$Ther$	Thermal
S	Sun

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