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IMPACT OF PARTIAL SHADING GEOMETRY ON THE ENERGY AND EXERGY PERFORMANCE OF PV MODULES

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Highlights

- The impact of shader form on PV module energy performance is studied.
- The rectangular form causes the greatest reduction in 1st and 2nd law efficiencies.
- The lowest diminish in the efficiencies has been obtained by triangular form.
- The highest efficiency decrease is 7.22% energetically, and 9.04% exergetically.

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ABSTRACT: In this experimental study, the impact of the geometric shape of partial shading on the energy and exergy performance of photovoltaic (PV) modules was evaluated using quadrant, triangular, and rectangular shaped shaders located on PV_1, PV_2, and PV_3 modules. The change in power output as well as the first and second efficiency of the PV modules was examined. In addition, fluctuations in the cost of exergy destruction ($COEx$) and the sustainability index (SI) were also observed. As a result, while the first law efficiencies of the PV_1, PV_2, and PV_3 modules were determined to be 5.33%, 6.85%, and 4.97%, respectively, the second law efficiencies were calculated as 2.06%, 3.99%, and 1.38%, respectively. The decrease rate of the first law efficiencies of the PV_1, PV_2, and PV_3 modules compared to the PV module was 6.86%, 5.34%, and 7.22%, respectively. Likewise, the decline in the second law efficiencies of the PV_1, PV_2, and PV_3 modules was 8.36%, 6.43%, and 9.04%, respectively. The $COEx$ for them was \$29.89/year, \$29.34/year, and \$30.11/year, respectively, while for the PV module it was \$29.01/year. The SI of the PV_1, PV_2, and PV_3 modules is 8.92%, 7.14%, and 9.82% lower than that of the PV module.

Keywords: *Energy, Exergy, First And Second Law Efficiency, Partial Shader Geometry, SI*

1. INTRODUCTION

Currently, 81% of the world's energy needs are met by fossil fuels. The fossil fuel demand provided by 26.8% coal, 23.2% natural gas and 30.9% petroleum. The share of renewable energy sources is below 15% [1]. Population growth increases energy demand, but political and economic crises limit access to energy sources. Because of the threat to their national energy security, nations are turning their attention to alternatives like renewable energy sources [2]. The most common, widely accessible and easily convertible renewable energy source is solar energy [3]. Compared to other energy sources, solar energy is incredibly affordable because of its low initial investment, ongoing maintenance, and operating costs. [4]. Systems that run on solar energy have nearly zero CO_2 emissions, making them significantly better for the environment than systems that use carbon-intensive energy sources. PV cells, semiconductor structures that convert sunlight directly into electricity, are a widely used technology [5]. The energy conversion efficiency of a PV module can be increased to a limited extent by reducing its temperature. In addition, this enhancing effect further increases effectiveness with increased sunlight [6]. A few examples of dynamic environmental factors that impact PV module performance are temperature variations, partial shading, and fluctuating solar irradiance [7]. Shade drastically lowers PV power output by blocking sunlight from reaching the PV module [8]. The energy conversion of PV modules can be influenced by two types of shading: static and dynamic. While static shading can be produced by things like buildings, trees, and signs, dynamic shading can be produced by clouds, birds, or flying objects in the air [9]. To achieve high voltage, PV cells in PV modules must be connected in series; However, this also limits the system current because the cell with the lowest current among the cells connected in series also acts as a current limiter. This is why shading a PV cell can limit the total current of the series. Connecting a string of parallel bypass diodes to a cell string will eliminate this restriction [10]. Partial shading has no discernible effect on the total voltage of the cells connected in series, which is the sum of all the voltages [11]. Shaded PV cells also produce lower current and are forced to carry higher current resulting from unshaded cells. When the operating current exceeds the short-circuit current in shaded cells, hotspot

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heating occurs, an area of PV modules that becomes overheated due to shading, resulting in premature degradation and permanent damage to the shaded cells [12], [13]. PV cells that are partially shaded produce a resistance that acts as a load rather than generating electricity. Bypass diodes are used to eliminate these shaded cells and facilitate easy transfer of the current generated by the non-shaded cells [14]. The following lines provide a detailed overview of the studies that address the effects of shading on the module performance. A study conducted by Sathyanarayana et al. examined how shading affects the output power and energy efficiency of a PV module. It was found that a 2.46% reduction in energy efficiency was caused by almost 19.82% shading of the module surface [15]. The study by Bayrak et al. investigated the effects of shading size on the performance of a PV module. It was found that the module efficiency decreases by 0.78%, 4.16%, 4.45% and 5.26% at shading rates of 25%, 50%, 75% and 100%, respectively [16]. Belhus's et al. have found that partial shading can significantly reduce the power output of PV module arrays. They added that the shading pattern may be more important in this case than the shading area alone [17]. Hariharasudhan et al. conducted an experiment to study the performance of PV modules under different partial shading conditions for individual PV cells. They found that the performance drop is almost 26% [18]. A study by Trammel et al. examined energy losses from PV modules due to shading or pollution. Partial shading of a PV module, they explained, is not as bad as shading the entire cell, which can cause the system to lose up to 25% of its power [19]. An article by Bellhouse et al. investigated the close relation between the effects of partial shading and the performance of PV modules. They tried to mitigate the effects of partial shading on the energy efficiency of the PV systems [20]. In a study, Tian et al. concluded that even minimal shading can significantly reduce the electrical output of a PV system [21]. In a study by Mamun et al. investigated the effect of partial shading on the energetic performance of a PV module. It has been reported that a 10% increase in shaded module area results in a 2.3% reduction in electrical efficiency [22]. In an experimentally validated computational study by Cameron et al., it was found that partial shading can lead to a decrease in the exergy efficiency of a PV module by approximately 3.5% [23]. Bayrak and Oztop investigated the influence of the shading size of both static and dynamic shading on the performance of the PV module. They evaluated hotspot formation and compared the performance degradation [24]. In an experimental study by Keskin, partial shading of a PV string was found to reduce exergy efficiency by approximately 6.87% [25]. A study by Dolara et al. investigated how partial shading affects the energetic performance of the PV modules. Their findings indicate that power output is lowered by over 30% when a single cell is shaded by 50% [26]. In an experimental study, Tripathi et al. found that the power reduction was almost 70.27% when half of the PV module area was shaded [27]. The studies mentioned so far, along with many others in the literature, address the decline in the energetic performance of PV systems due to shading. A large part of it specifically addressed the question of whether shadow size has a serious impact on performance degradation. Few of them have considered that in addition to shadow size, shadow geometry can also have an impact on performance degradation. Through this consideration, this study, conducted with shaders with identical shadow areas and different geometric forms, attempts to contribute to the literature on the impact of shadow geometry on performance degradation.

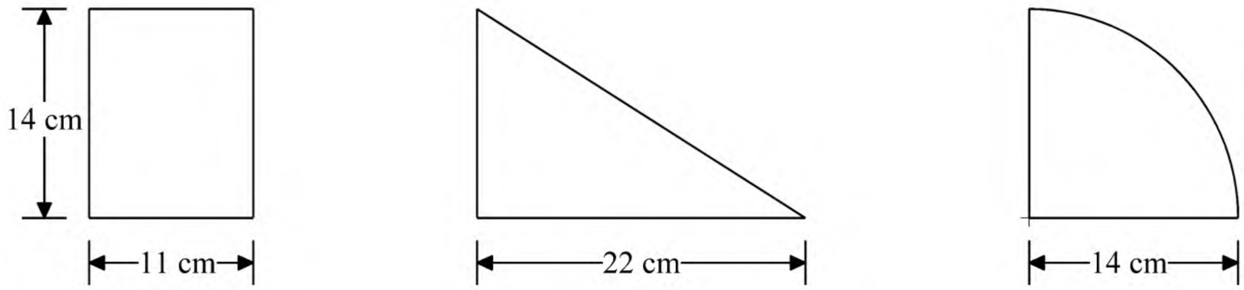
2. MATERIALS AND METHODS

The effects of partial shading geometry on the energy and exergy performance of PV modules were experimentally investigated in this study. The study was conducted in the city of Karabuk in the western part of the Black Sea region of Türkiye. The test was conducted on a bright, cloudless day in January 2024. The test took place between 11:00 and 16:30. Four identical PV modules with a peak output of 50 W are used for the test. In Table 1, the PV module specifications were shown.

Table 1. PV module specifications.

Module type	Monocrystalline
Dimensions (cm)	67.4 x 42.4 x 2.5
Rated peak power (W_P)	50
Tolerance (%)	±5
Peak power voltage (V)	20.6
Peak power current (A)	2.43
Circuit voltage [open] (V)	22.68
Circuit current [short] (A)	2.37
All data is for standard conditions of testing; AM 1.5, T_c=25°C, F=1000 W/m²	

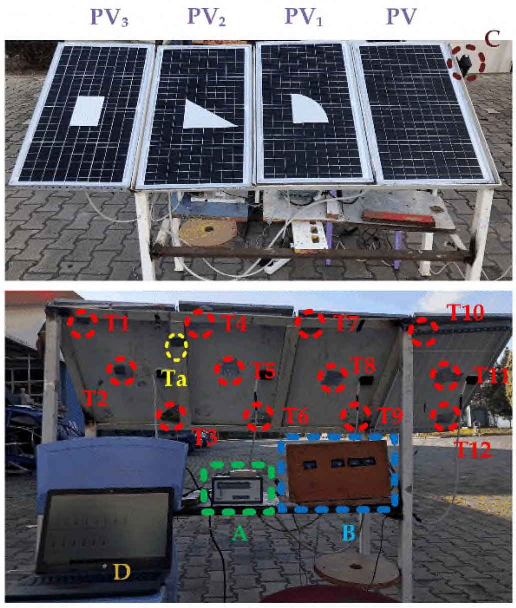
The PV modules in the test setup were optimally oriented to the south with a fixed tilt angle of 40°, which was the ideal position in Karabuk. To create the shading effect, three differently shaped shaders (quadrant, triangular, and rectangular) were cut out of thick paper with the same surface area. Figure 1 shows the dimensions of the shaders. The area of each piece is 154 cm². Each piece was placed in an identical position on the PV modules. The first PV module is the reference module. The shaders in the shape of a quadrant, a triangular and a rectangular were positioned at the same locations of the PV_1, PV_2 and PV_3 module surface, respectively.



(a) (b) (c)

Figure 1. Dimensional details of shading form a) rectangle, b) triangle, c) quadrant.

The electric outputs of the PV modules were linked to a load circuit equipped with resistors and digital voltmeters/ammeters. To test each module under load, 50W 14.7Ω resistors were used. Solar irradiance was measured using the TES 1333R solar power meter. K-type thermocouples were attached to the rear of each module to monitor its temperature. Two of the thermocouples were positioned at opposite corners of the module, with the third in the middle. Due to the uneven temperature distribution of the modules during testing, we estimated the temperature of each module by averaging its three-point data. The ambient temperature was measured using a K-type thermocouple. Data collected from thermocouples using an Elimko E680 data logger were recorded on a computer. Every second, the data logger transmitted temperature readings to a computer. For evaluation, half-hourly time averages of the data were calculated. Voltage, current and solar irradiance data were recorded every 30 minutes throughout the test. The test setup was shown in detail in Figure 2.



A – Elimko E680 datalogger
B – Load circuit with voltmeter and ammeter
C – TES 1333R solar power meter
D – Computer
T – Temperature measurement point

Figure 2. An illustration of the experimental setup in detail.

Table 2 lists the measuring devices with their technical specifications.

Table 2. Measuring instruments and their technical capabilities

Device / Sensor	Data type	Measurement point	Specifications	Uncertainty (%)
Elimko E680 data logger / Picotech, K-type thermocouple	Temperature	T1, T2, T3, T4, T5, T6, T7, T8, T9, T10, T11, T12, Ta	Measurement range: -200 to +1300°C / -40 to 1200°C	±0.5 / ±2.5
Load circuit with voltmeter and ammeter	Voltage and current	Module electrical outputs	Measurement range: DC 0 to100 V, 0 to 10 A	±1
TES 1333R solar power meter	Solar irradiance	C	Measurement range: 0 to 2000 W/m²	±5

The experimental uncertainty of the study was determined using the terminology described in the "Uncertainty Model" section below.

2.1. Uncertainty Model

The uncertainty of the results, which depends on the uncertainty of the measurement data, was determined by uncertainty analyzes using the Kline and McClintock method, which is given in Eq. (1) [16].

$$w_R = \sqrt{\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2} \quad (1)$$

In Eq. (1), R is the functional relationship of the independent variables $x_1, x_2, \cdots, x_n$. The resulting uncertainty is denoted by w_R. $w_1, w_2, \cdots, w_n$ are the uncertainty of independent variables. The calculated overall uncertainty of the test was determined to be 5.92%. The data evaluation of the experimental measurements was carried out based on the theoretical relationships specified in the following "Mathematical Model" section.

2.2. Mathematical Model

Using the relationships found in Eqs. (1–9), PV modules can be examined from an energy perspective. The energy balance of the PV modules is given by Eq. (2) [28].

$$\dot{P}_s = \dot{P}_e + \dot{P}_{th,l} + \dot{P}_{oth,l} \quad (2)$$

In Eq. (2), $\dot{P}_s$ and $\dot{P}_e$ denote the solar and electrical energy rates. $\dot{P}_{th,l}$ is the thermal energy lost to the environment in the test configuration. $\dot{P}_{oth,l}$ symbolize the other losses of the PV module to the environment. Eq. (3) presents solar energy [28].

$$\dot{P}_s = G_s A f_{act} \quad (3)$$

Where A is the PV module surface area, G_s is the solar irradiance. Active module surface fraction is represented by f_{act}. Eq. (4) relates to the electrical power that a PV module produces [29].

$$\dot{P}_e = IV \quad (4)$$

Where I and V represent the current and voltage outputs of a PV module. Eq. (5) indicates the thermal losses of a PV module [29].

$$\dot{P}_{th,l} = hA\Delta T \quad (5)$$

The overall heat transfer coefficient (h) is determined using Eq. (6) [29].

$$h = h_c + h_r \quad (6)$$

Equation for the convection heat transfer coefficient (h_c) as in Eq. (7) [29].

$$h_c = 2.8 + 3V_w \quad (7)$$

Where V_w symbolizes the local wind speed. Eq. (8) is used to calculate the radiative heat transfer coefficient (h_r) [29].

$$h_r = \varepsilon\sigma\left(T_{sky} + T_m\right)\left(T_{sky}{}^2 + T_m{}^2\right) \quad (8)$$

In Eq. (8), emissivity constant, Stefan-Boltzmann constant and module temprature are indicated by the symbols ε, σ, and T_m. Eq. (9) can be used to estimate the effective temperature of the sky (T_{sky}) [29].

$$T_{sky} = T_a - 6 \quad (9)$$

Where the ambient temperature is denoted by T_a. First law efficiency (η_I) of a PV module is determined by the relationship according to Eq. (10) [29].

$$\eta_I = \frac{\dot{P}_e}{\dot{P}_s} \quad (10)$$

Eqs. (10–15) are used to examine PV modules from an exergy perspective. The exergy balance of the PV module is defined using Eq. (11) [29].

$$\sum \dot{Ex}_i = \sum \dot{Ex}_o + \sum \dot{Ex}_l + \sum \dot{Ex}_{ir} \quad (11)$$

Where, $\dot{Ex}_i$, $\dot{Ex}_o$, $\dot{Ex}_l$ and $\dot{Ex}_{ir}$ indicates input, output, loss exergy rates and the irriversibility rate. Solar exergy rate ($\dot{Ex}_s$) is shown in Eq. (12) [29].

$$\dot{Ex}_s = \dot{P}_s \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] \quad (12)$$

Where, (T_s) denotes the sun temperature. Electical exergy rate ($\dot{Ex}_e$) is defined by Eq.(13) [29].

$$\dot{Ex}_e = \dot{P}_e \quad (13)$$

In this study, the thermal exergy rate ($\dot{Ex}_{th}$) is lost to the environment and cannot be used. For this reason, it is related to heat loss and is expressed as in Eq. (14) as follows [29].

$$\dot{Ex}_{th} = \dot{P}_{th,l}\left(1 - \frac{T_a}{T_m}\right) \quad (14)$$

The exergy loss can be calculated by Eq. (15) [30].

$$\dot{Ex}_l = \dot{Ex}_s(1 - \eta_{II}) \quad (15)$$

Eq. (16) provides the PV module efficiency (η_{II}) based on the second law of thermodynamics [16], [31]–[34].

$$\eta_{II} = \frac{\dot{Ex}_o}{\dot{Ex}_i} = \frac{\dot{Ex}_e - \dot{Ex}_{th}}{\dot{Ex}_s} \quad (16)$$

Where input and output exergies are indicated by the symbols $\dot{Ex}_i$ and $\dot{Ex}_o$. Eq. (17) shows the relationship between the SI, the evaluation parameter of exergy applications to reduce resource waste and environmental damage, and the second law efficiency [35].

$$SI = \frac{1}{1 - \eta_{II}} \quad (17)$$

The $COEx$ can be computed using Eq. (18) [32].

$$COEx = unit\ price\ of\ electricity\ \times destructed\ exergy \tag{18}$$

The measured and calculated energy and exergy-based data related to the stated theoretical basis in this section were evaluated in the next section "Results and Discussions".

3. RESULTS AND DISCUSSIONS

This experimental study investigated the effects of partial shading with identical area but different shadow shape on the energy and exergy performance of PV modules. In the following section, authors visualized, and evaluated the measured and calculated electrical, thermal, and energetic parameters. The solar irradiance, ambient temperature, and PV module temperatures are shown in Figure 3. As indicated by the graphic curves in Figure 3, the solar irradiance was 525.4 W/m² at 11:00, the start of the test. At 14:30, the irradiance reached its maximum value of 1124 W/m², after increasing gradually until midday. The irradiance decreased with a more noticeable decreasing trend from 14:30 to 16:30, reaching the value of 646 W/m², in contrast to the increase that was seen until 14:30. The test mean value of solar irradiance was 842.7 W/m². The average ambient temperature for the test day was calculated to be 6°C using the data shown in Figure 3. Before testing, the setup was kept in a dark, closed environment. For this reason, at the start of the test, the test setup was close to ambient temperature and the PV modules were at the same temperature. PV modules start converting energy as soon as they are exposed to sunlight and their temperature increases accordingly. PV cells that are partially shaded produce less current than those that are not. By blocking the high current that tries to pass through them, shaded cells function as a reverse p-n junction, lowering the circuit voltage, heating up, producing hot spots, and releasing energy [36]. As shown in Figure 3, hotspots caused by different current resistances due to different shading geometries under the same conditions resulted in temperature fluctuations between the partially shaded PV_1, PV_2 and PV_3 modules compared to the unshaded PV module. Compared to the unshaded PV module, the temperatures of the shaded modules were even higher. The average PV module temperature was found to be 22°C, while the average PV_1, PV_2, and PV_3 temperatures were 25°C, 24°C, and 26°C, respectively. Partial shading limited the solar irradiance on the PV cells and the hotspots resulted in differences in the module temperatures, which affected the current and voltage outputs of the PV modules.

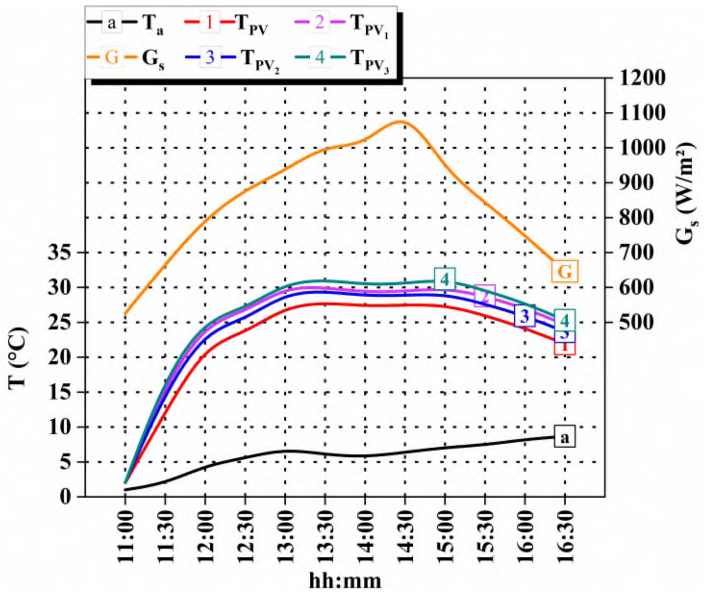


Figure 3. The solar irradiance on test day and the temperatures of the modules and surroundings.

As show in Figure 4, the output voltage and current of the PV modules. Figure 4 shows that module outputs tended to increase until midday as solar irradiance increased. A downward trend in the outputs was noted as the irradiance intensity incident on the panels began to decrease over the following hours of testing. Based on the data in Figure 4, the average voltage and current outputs for the PV were determined to be 20.74 V and 1.39 A. The partially shaded PV_1, PV_2 and PV_3 modules had average output voltages of 13.46 V, 15.18 V and 12.89 V, respectively. Their respective average output currents were 0.9 A, 1.02 A, and 0.88 A. It was found that the electrical performance of partially shaded modules is significantly lower than that of unshaded module. Compared to the PV module, the voltage outputs of the PV_1, PV_2 and PV_3 modules decreased by about 35.11%, 26.79% and 37.84%, respectively. In that order, current production fell by 34.93%, 26.35% and 36.73%. The shader with the rectangular shape reduced voltage and current the most, while the shader with the triangular shape reduced them the least. Since the PV module was not shaded, sunlight could reach the PV cells unhindered, exposing the entire surface to the sun. All of the solar irradiance and, thus, all of the solar power could not reach the PV cells due to the partial shading of the PV_1, PV_2, and PV_3 modules.

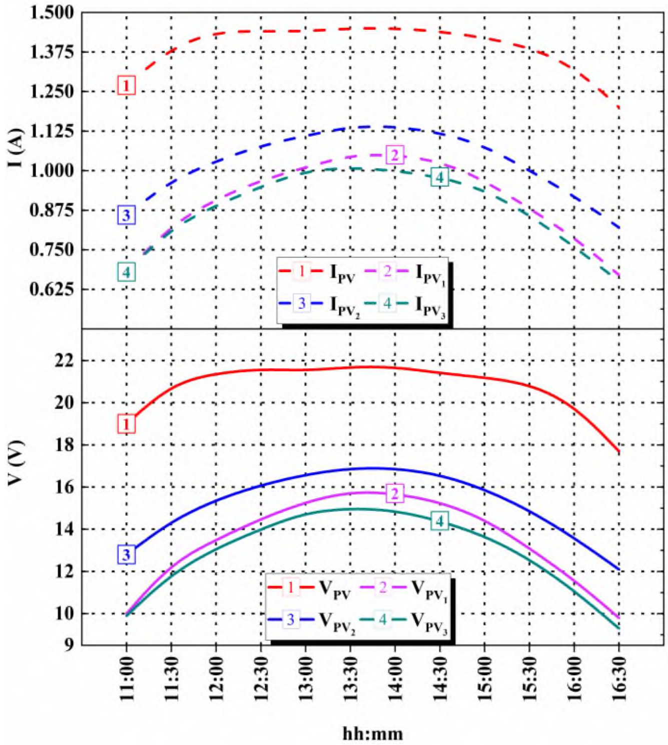


Figure 4. Current and voltage outputs of PV modules.

The half-hourly values of solar power reaching the module cells and the electrical power outputs of the module are shown in Figure 5. Solar irradiance increased, the solar power on the PV modules increased with a decreasing trend until 14:30, and then showed a stable decreasing trend until the end of the test as shown in Figure 5. The PV module received an average of 242.78 W of solar power because it was not shaded, while the PV_1, PV_2 and PV_3 modules only received an average of 229.81 W due to the shade. On average, 28.89W of solar energy could be converted into electricity by the PV module, while 12.42W, 15.69W and 11.55W could be converted by PV_1, PV_2 and PV_3, respectively. Partial shading of modules with shaders of the same size, which reduced the amount of solar irradiance reaching the module cells by approximately 5.34%. However, the loss of electrical power was significantly higher due to the resulting current resistance and hotspots in the shaded cells. The average electrical power output of PV_1, PV_2 and PV_3 recorded a decrease of 57%, 45.68% and 60.01%, respectively. In an experimental study by

Abdulmawjood et al., a reduction in output power ranging from 45.8% to 72.6% was observed by changing the shading area [37].

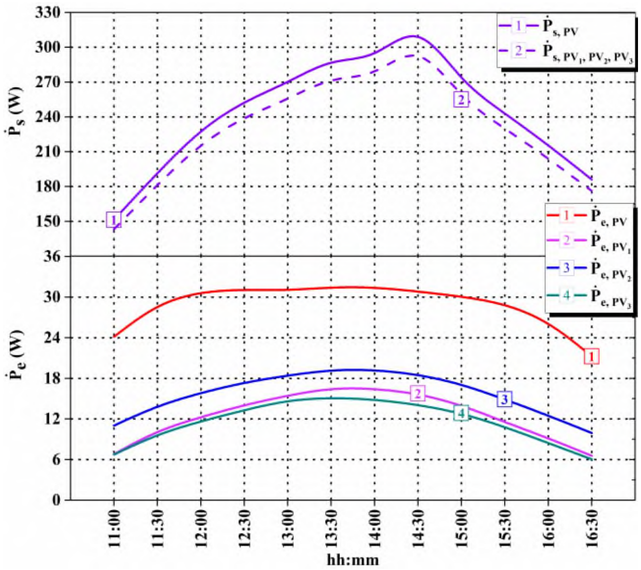


Figure 5. The solar power and the electrical power outputs

In terms of electrical power output, the triangular shader had the smallest reduction and the rectangular shader had the largest. Figure 6 shows the input, output and loss exergies of PV modules. The input exergy rate of the PV module was 227.14 W, the output exergy rate was 22.57 W, and the loss exergy rate was calculated to be 204.58 W, as shown in Figure 6. The input exergy rate of the PV_1, PV_2 and PV_3 modules decreased to 215.01 W due to partial shade. All three partially shaded modules experienced an equal decrease in input exergy rate of approximately 5.34% compared to the PV module. The PV_1, PV_2 and PV_3 modules were found to have output exergy rates of 4.21 W, 8.12 W and 2.65 W, respectively. According to the calculations, the exergy loss rates were 210.8 W, 206.88 W and 212.35 W in that order. Compared to the PV module, the output exergy rates of the PV_1, PV_2 and PV_3 modules shaded by a quadrant, a triangular and a rectangular partial shaders decreased by 81.34%, 64.02% and 88.25%, respectively. The hotspot created due to the shading increased the loss exergy by about 3.04%, 1.08% and 3.79% in PV_1, PV_2, and PV_3, respectively. In an experimental study of Khajen and Keskin, the maximum increase in exergy loss due to the shading effect was found to be 23.32% [38]. The triangular formed partial shader displayed the least amount of reducing effect, whereas the rectangular formed partial shader decreased the exergy output rate in the maximum rate despite having equal surface areas.

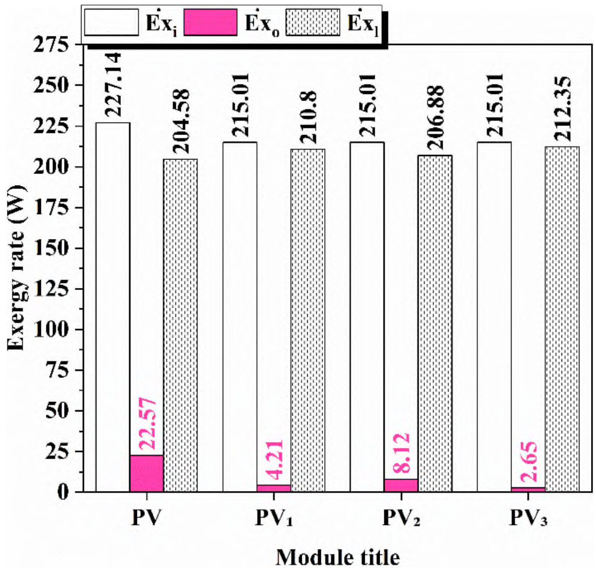


Figure 6. Input, output and loss exergy of PV modules.

The energy and exergy efficiencies of the modules are shown comparatively in Figure 7. The first and second efficiencies of the PV module reached 12.19% and 10.42% in the test, respectively, as shown in Figure 7. In addition, Figure 7 shows that the first law efficiency of the PV_1, PV_2 and PV_3 modules compared to the PV module was affected to different extents by partial shaders with different geometric shapes, equivalent surface areas and the same positioning on the module surfaces. PV_1, PV_2, and PV_3 modules had first law efficiencies of 5.33%, 6.85%, and 4.97%, respectively; second law efficiencies were 2.06%, 3.99%, and 1.38%, in that order. The first law efficiency of PV_1, PV_2 and PV_3 modules decreased by 6.86%, 5.34% and 7.22%, respectively, compared to the PV module. The second law efficiency values for the PV_1, PV_2 and PV_3 modules decreased by 8.36%, 6.43% and 9.04%, respectively. PV_2 and PV_3 modules shaded by triangular and rectangular shaders showed the lowest and highest changes in first and second law efficiency, respectively.

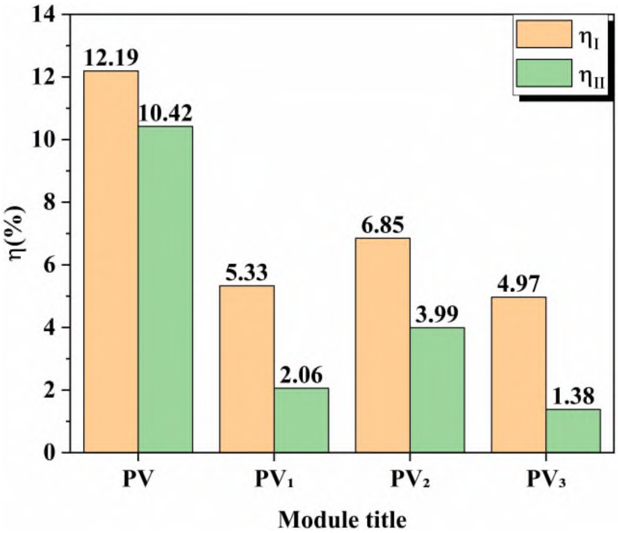


Figure 7. The first and second law efficiencies of modules.

Another notable aspect besides the variation in energy and exergy efficiency values is that the energy efficiency values for each module are greater than the exergy efficiency values. The reason for this common situation is explained in detail in Refs. [34], [39]–[43] as follows: Energy efficiency, based on the first law of thermodynamics, deals with the quantity of energy and does not consider irreversibility. However, exergy efficiency, which is associated with the second law of thermodynamics, evaluates the quality of energy and is only interested in the energy that can be used for useful purposes at the end of the process. When evaluating exergy efficiency, the part of solar energy that is converted into electrical energy in PV cells is evaluated as output energy, and the part that is converted into heat is evaluated as a loss, not as output. At this point, it is concluded that the exergy efficiency of a PV module is always lower than the energy efficiency, which is because of irreversibilities. The energy and exergy efficiencies of this study were summarized in Table 3 by comparing the results of similar studies from literature.

Table 3. Comparison of energy and exergy efficiency based on similar study results in literature.

Study	Method	Type of shading	η_I (%)		η_{II} (%)	
			Unshaded	Shaded	Unshaded	Shaded
This study	Experimental	Static shading	12.19	6.85	10.42	3.99
Bayrak et al. [16]			8.19	5.3	8.05	4.86
Gurturk et al. [44]			2.53	2.19	1.7	1.46
Khalejan and Keskin [38]		Dynamic shading	9.12	8.79	7.82	6.87

The energy and exergy efficiency results of this study tend to vary similarly to the results of the literature supporting the results and presented in Table 3. The electricity tariff fee set by the Energy Market Regulatory Authority of the Republic of Türkiye that energy suppliers charged for residential customers from January 1, 2024 is 5.8 cents/kWh [45]. The authors calculated the cost of exergy loss based on the electricity price. They visualized the SI and $COEx$ in Figure 8. The estimated annual $COEx$ for a PV module was \$29.01, as shown in Figure 8. PV_1, PV_2, and PV_3 had $COEx$ values of \$29.89, \$29.34, and \$30.11 annually, respectively. The triangular shader caused a minimal increase in the $COEx$, while the rectangular shader caused a maximal increase. The PV module had a SI of 1.12, while the PV_1, PV_2, and PV_3 modules had SI of 1.02, 1.04, and 1.01, respectively. Compared to the PV module, the SI of the PV_1, PV_2 and PV_3 modules decreased by 8.92%, 7.14% and 9.82%, respectively. The decline effect was observed in the SI through the shading effect in an experimental study by Khan et al. [46]. The triangular shader caused the smallest drop in the SI due to shading, while the rectangular shader caused the largest drop. The decline in the SI can be related to the increase in $COEx$.

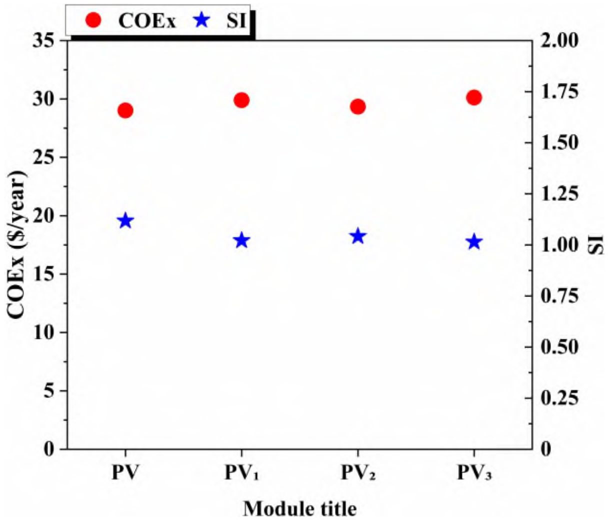


Figure 8. The $COEx$ and SI of the modules.

The general judgment obtained from all these evaluations is summarized and presented in the last section, "Conclusions".

4. CONCLUSIONS

In this experimental study, the effect of the geometric shape of partial shading on the energy and exergy performance of PV modules was examined using a four-module test setup. One module was unshaded (referred to as a PV module), the others were shaded with quadrant, triangular, and rectangular shaped shaders and called PV_1, PV_2, and PV_3, respectively. The test conducted in Karabuk, Türkiye found that the shaded panels (PV_1, PV_2 and PV_3) received less solar power. Shading reduced the power generation of the shaded cells, increased resistance in the circuit, and limited current flow, which in turn reduced the performance of the modules. Furthermore, local hotspots caused by resistance in shaded cells could potentially lead to long-term irreparable damage. Below is a detailed numerical summary of the effects of shading geometry on the energy and exergy performance of PV modules based on experimental measurements and calculations.

- The first and second efficiencies of the PV module were 12.19% and 10.42%, respectively.
- The PV_1, PV_2, and PV_3 modules had first law efficiencies of 5.33%, 6.85%, and 4.97%, respectively.
- The second law efficiencies of the PV_1, PV_2, and PV_3 modules were 2.06%, 3.99%, and 1.38%, respectively.
- In the PV_1, PV_2, and PV_3 modules, the first law efficiencies decreased by 6.86%, 5.34%, and 7.22%, respectively.
- The second law efficiencies for modules PV_1, PV_2, and PV_3 decreased by 8.36%, 6.43%, and 9.04%, respectively.
- The annual value of $COEx$ for PV_1, PV_2, and PV_3 was \$29.89, \$29.34, and \$30.11, respectively, while the value for PV module was \$29.01.
- The SI decreased by 8.92%, 7.14%, and 9.82% for PV_1, PV_2, and PV_3 modules compared to PV module, respectively.

Declaration of Ethical Standards

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

Credit Authorship Contribution Statement

Saleh Musaed Saleh ALNAKHLANI : Resources, Methodology, Experimentation, Investigation.
Selcuk SELİMLİ: Methodology, Writing – original draft, Visualisation, Supervision, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The research data has not been made available in the repository.

REFERENCES

[1] L. Xu, P. Ding, Y. Zhang, Y. Huang, J. Li, and R. Ma, "Sensitivity analysis of the shading effects from obstructions at different positions on solar photovoltaic panels," *Energy*, vol. 290, p. 130229, 2024.
[2] B. A. Kazancı, O. F. F. Arslan, and S. Dincer, "Climate Crisis and The Future of Renewable Energy in the Turkic Republics," in *Analyzing Energy Crises and the Impact of Country Policies on the World*, M. S. O. Ozcan, Ed., 1st ed.IGI Global, 2023, pp. 178–194.
[3] N. L. Panwar, S. C. Kaushik, and S. Kothari, "Role of renewable energy sources in environmental protection: A review," *Renew. Sustain. Energy Rev.*, vol. 15, no. 3, pp. 1513–1524, 2011.
[4] M. K. H. Rabaia *et al.*, "Environmental impacts of solar energy systems: A review," *Sci. Total Environ.*, vol. 754, p. 141989, 2021.
[5] L. Etgar, "Semiconductor nanocrystals as light harvesters in solar cells," *Materials (Basel).*, vol. 6, no. 2, pp. 445–459, 2013.
[6] S. P. Aly, S. Ahzi, and N. Barth, "Effect of physical and environmental factors on the performance of a photovoltaic panel," *Sol. Energy Mater. Sol. Cells*, vol. 200, p. 109948, 2019.
[7] K. Suresh Kumar and P. Winston David, "Performance analysis of winnowing dynamic reconfiguration in partially shaded solar photovoltaic system," *Sol. Energy*, vol. 268, p. 112309, 2024.
[8] K. Hasan, S. B. Yousuf, M. S. H. K. Tushar, B. K. Das, P. Das, and M. S. Islam, "Effects of different environmental and operational factors on the PV performance: A comprehensive review," *Energy Sci. Eng.*, vol. 10, no. 2, pp. 656–675, 2022.
[9] S. K. Das, D. Verma, S. Nema, and R. K. Nema, "Shading mitigation techniques: State-of-the-art in photovoltaic applications," *Renew. Sustain. Energy Rev.*, vol. 78, pp. 369–390, 2017.
[10] S. Gallardo-Saavedra and B. Karlsson, "Simulation, validation and analysis of shading effects on a PV system," *Sol. Energy*, vol. 170, pp. 828–839, 2018.
[11] P. dos Santos Vicente, E. M. Vicente, M. G. Simoes, and E. R. Ribeiro, "Shading position effects on photovoltaic panel output power," *Int. Trans. Electr. Energy Syst.*, vol. 30, no. 1, pp. 1–19, 2020.
[12] M. Khodapanah, T. Ghanbari, E. Moshksar, and Z. Hosseini, "Partial shading detection and

hotspot prediction in photovoltaic systems based on numerical differentiation and integration of the P − V curves," *IET Renew. Power Gener.*, vol. 17, no. 2, pp. 279–295, 2023.

[13] K. Osmani, A. Haddad, H. Jaber, T. Lemenand, B. Castanier, and M. Ramadan, "Mitigating the effects of partial shading on PV system's performance through PV array reconfiguration: A review," *Therm. Sci. Eng. Prog.*, vol. 31, p. 101280, 2022.

[14] S. Hamdi, D. Saigaa, and M. Drif, "Modeling and simulation of photovoltaic array with different interconnection configurations under partial shading conditions for fill factor evaluation," in *Proceedings of 2014 International Renewable and Sustainable Energy Conference*, 2014, pp. 25–31.

[15] P. Satyanarayana, R. Ballal, L. P. Sagar S, and G. Kumar, "Effect of shading on the performance of solar PV panel," *Energy and Power*, vol. 5, no. 1A, pp. 1–4, 2015.

[16] F. Bayrak, G. Ertürk, and H. F. Oztop, "Effects of partial shading on energy and exergy efficiencies for photovoltaic panels," *J. Clean. Prod.*, vol. 164, pp. 58–69, 2017.

[17] N. Belhaouas *et al.*, "PV array power output maximization under partial shading using new shifted PV array arrangements," *Appl. Energy*, vol. 187, pp. 326–337, 2017.

[18] T. Hariharasudhan, D. Prince Winston, M. Palpandian, and M. Pravin, "A comparative analysis of polycrystalline and bifacial photovoltaic module under various partial shading condition," *Energy Convers. Manag.*, vol. 270, p. 116223, 2022.

[19] G. Trzmiel, D. Głuchy, and D. Kurz, "The impact of shading on the exploitation of photovoltaic installations," *Renew. Energy*, vol. 153, pp. 480–498, 2020.

[20] N. Belhaouas *et al.*, "A new approach of PV system structure to enhance performance of PV generator under partial shading effect," *J. Clean. Prod.*, vol. 317, p. 128349, 2021.

[21] H. Tian, F. Mancilla-David, K. Ellis, E. Muljadi, and P. Jenkins, "Determination of the optimal configuration for a photovoltaic array depending on the shading condition," *Sol. Energy*, vol. 95, pp. 1–12, 2013.

[22] M. A. Al Mamun, M. Hasanuzzaman, and J. Selvaraj, "Experimental investigation of the effect of partial shading on photovoltaic performance," *IET Renew. Power Gener.*, vol. 11, no. 7, pp. 912–921, 2017.

[23] W. J. Cameron, M. M. Alzahrani, J. Yule, K. Shanks, K. S. Reddy, and T. K. Mallick, "Effects of partial shading on thermal stress and exergetic efficiency for a high concentrator photovoltaic," *Energy*, vol. 288, p. 129818, 2024.

[24] F. Bayrak and H. F. Oztop, "Effects of static and dynamic shading on thermodynamic and electrical performance for photovoltaic panels," *Appl. Therm. Eng.*, vol. 169, p. 114900, 2020.

[25] V. Keskin, "Exergoeconomic analysis of a photovoltaic array affected by dynamic shading," *J. Sci. Reports-A*, no. 052, pp. 35–50, 2023.

[26] A. Dolara, G. C. Lazaroiu, S. Leva, and G. Manzolini, "Experimental investigation of partial shading scenarios on PV (photovoltaic) modules," *Energy*, vol. 55, pp. 466–475, 2013.

[27] A. K. Tripathi, M. Aruna, and C. S. N. Murthy, "Performance of a PV panel under different shading strengths," *Int. J. Ambient Energy*, vol. 40, no. 3, pp. 248–253, 2019.

[28] M. Abou Houran *et al.*, "Energy and exergy analysis of a novel solar-based system merged with power cycle," *Appl. Therm. Eng.*, vol. 240, p. 122080, 2024.

[29] C. Manjunath, J. Reddy, K. S. R. Reddy, I. R. G. Kumar, and S. Sanketh, "Energy, exergy performance and analysis of 50W solar photovoltaic module," *Mater. Today Proc.*, vol. 54, pp. 531–536, 2022.

[30] W. Zou, G. Yu, and X. Du, "Energy and exergy analysis of photovoltaic thermal collectors: Comprehensive investigation of operating parameters in different dynamic models," *Renew. Energy*, vol. 221, p. 119710, 2024.

[31] K. Sopian, A. H. A. Al-Waeli, and H. A. Kazem, "Energy, exergy and efficiency of four photovoltaic thermal collectors with different energy storage material," *J. Energy Storage*, vol. 29, p. 101245, 2020.

[32] S. Sukumaran and K. Sudhakar, "Performance analysis of solar powered airport based on energy and exergy analysis," *Energy*, vol. 149, pp. 1000–1009, 2018.

[33] W. Kuczynski and K. Chliszcz, “Energy and exergy analysis of photovoltaic panels in northern Poland,” *Renew. Sustain. Energy Rev.*, vol. 174, p. 113138, 2023.
[34] A. S. Joshi, I. Dincer, and B. V. Reddy, “Thermodynamic assessment of photovoltaic systems,” *Sol. Energy*, vol. 83, no. 8, pp. 1139–1149, 2009.
[35] M. Abid and A. Hepbasli, “Dynamic exergetic analysis and evaluation of photovoltaic modules,” *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 37, no. 21, pp. 2271–2284, 2015.
[36] A. Saha, N. N. Nipu, and M. F. Khan, “Effect of partial shading on the performance of solar PV module and impact of bypass diode in performance enhancement,” in *2019 5th International Conference on Advances in Electrical Engineering (ICAEE)*, 2019, pp. 891–896.
[37] K. Abdulmawjood, S. Alsadi, S. S. Refaat, and W. G. Morsi, “Characteristic study of solar photovoltaic array under different partial shading conditions,” *IEEE Access*, vol. 10, pp. 6856–6866, 2022.
[38] S. H. Pour Rahmati Khalejan and V. Keskin, “Effects of dynamic shading on thermal exergy and exergy efficiency of a photovoltaic array,” *Teh. Vjesn. - Tech. Gaz.*, vol. 29, no. 6, pp. 1889–1895, 2022.
[39] M. Yaghoubirad, N. Azizi, A. Ahmadi, Z. Zarei, and S. F. Moosavian, “Performance assessment of a solar PV module for different climate classifications based on energy, exergy, economic and environmental parameters,” *Energy Reports*, vol. 8, pp. 15712–15728, 2022.
[40] A. Pandey, P. Pant, O. Sastry, A. Kumar, and S. Tyagi, “Energy and exergy performance evaluation of a typical solar photovoltaic module,” *Therm. Sci.*, vol. 19, no. 2, pp. 625–636, 2015.
[41] A. R. Hakim, W. T. Handoyo, and P. Wullandari, “An energy and exergy analysis of photovoltaic system in Bantul Regency, Indonesia,” *J. Mechatronics, Electr. Power, Veh. Technol.*, vol. 9, no. 1, pp. 1–7, 2018.
[42] D. Rusirawan, “Energetic modelling of photovoltaic modules in grid-connected systems,” Ph.D. dissertation, Dept. of Mech. Eng., Szent István Univ.,Gödöllő, Hungary, 2012.
[43] K. N. Shukla, S. Rangnekar, and K. Sudhakar, “A comparative study of exergetic performance of amorphous and polycrystalline solar PV modules,” *Int. J. Exergy*, vol. 17, no. 4, pp. 433–455, 2015.
[44] M. Gurturk, H. Benli, and N. K. Erturk, “Effects of different parameters on energy - Exergy and power conversion efficiency of PV modules,” *Renew. Sustain. Energy Rev.*, vol. 92, pp. 426–439, 2018.
[45] Energy Market Regulatory Authority (EMRA), “Activity-based tariffs approved by EMRA and will be applied as of January 1, 2024,” 2024. [Online]. Available: https://www.epdk.gov.tr/Detay/DownloadDocument?id=59UJUGOnkMs=. [Accessed Sept. 17, 2024].
[46] M. A. Z. Khan, A. Wahab, F. Ali, N. Ahmad, M. A. Kamran, and A. Hassan, “Performance of solar roof top panels with disparate particulate accumulation: Exergy analysis on an indoor lab study,” *PLoS One*, vol. 18, no. 9, pp. 1–22, 2023.