Kütahya Dumlupınar University
Institute of Graduate Studies

Journal of Scientific
Reports-A
E-ISSN: 2687-6167
Number 52, March 2023

RESEARCH ARTICLE

EXERGOECONOMIC ANALYSIS OF A PHOTOVOLTAIC ARRAY AFFECTED BY DYNAMIC SHADING

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Receive Date:02.11.2022 *Accepted Date: 14.01.2023*

ABSTRACT

Photovoltaic (PV) panels are affected by undesirable elements that exist around them, trees, structures, clouds, etc., as well as natural dirt, and dust accumulation on the PV surfaces. Unfortunately, partial shading falling on top of the PV panels may affect badly the output of photovoltaic arrays. In this study, an exergoeconomic analysis has been performed on the impact of dynamic partial shading created by a mislocated building on a photovoltaic array. Both experimental and theoretical results of this study have been compared on ambient temperature, solar radiation intensity, and shading ratio. The observations have been carried out on clear days starting in June 2018 to Mai 2019. According to the results, the shaded PV exergy efficiency (6.87%) and exergoeconomic parameter (R_{ex}= 0.18508 W/$) are maxima in June and minimum in February (E_x =4.76%, R_{ex}= 0.12228 W/$). As a result of this study, it can be said that the PV array exposed to long-term shading will seriously affect the service life of the PV array.

Keywords: *Photovoltaics, Exergy, Exergoeconomic, Dynamic Shading*

1. INTRODUCTION

The growth and development of the human population, and in turn the demand-based energy requirement is increasing exponentially. In addition, environmental and climate problems caused by unconscious consumption have made it necessary to switch to sustainable, clean, and cheap energy. To provide a sustainable life for people and living things, cheaper and unlimited renewable energy sources have become more and more popular in the ever-increasing and so expensive electricity production. The energy produced from photovoltaic panels is becoming more and more popular because of this feature and because it is powered by the sun, which is clean, free, and inexhaustible. Photovoltaic panels, which are the basic components of solar power plants, are the most basic component that converts the energy from the sun as electricity that is usable energy everywhere. The photovoltaic power system is different from other renewable power generation systems and is more attractive because it has fewer moving parts in its structure. Unfortunately, photovoltaic panels are adversely affected by factors such as clouds, nearby trees, neighboring structures, dirt, misdirection, and slopes that cause partial shading on their front surfaces [1]. The shading falling on the PV array surface for different reasons may cause a decrease in the power production, but may also cause hot spots on the PV cells and even damage and so shortening their service life. The effect of shading by different obstacles and conditions on PV systems has been studied by many researchers [2-6].

Here are some well-known studies on shading and its effect, in chronological order; Bidram et al. [2] examined the negative effects of different PV array configurations, different PV system architectures, PV circuit topologies, reducing of electrical characteristics and hot spot events under partial shading. Dollar et al. [3] carried out experiments with PV modules produced from two different materials, on clear and sunny days, by creating graphs with the created current, voltage, and power parameters. He suggested that experimental analyzes with mathematical models are applied to estimate the lost power of the photovoltaic arrays. Chepp et al. [4] created a straightforward approach to assess how PV systems and modules perform when partially shaded. The proposed method's accuracy was contrasted with the approaches they selected, and I-V and performance values were examined. The variations between the results from the measurements and the models are quite close to 5%. A numerical and experimental study on partial shading detection was conducted by Khodapanah et al. [5]. It is feasible to discern between temporary and permanent shade conditions, the severity of the shading level, and, consequently, the time at which hot spots emerge using the technique they offer. The results of their investigation support their assertion that they can give partial shading detection without adding additional cells or modules to the system.

Recently, applying thermodynamics and environmental and economic analysis methods such as exergy and exergoeconomic analysis has been increasing. Mostly, the performance evaluations of PV power systems are made with the energy analysis method. Moreover, the exergy analysis method is more detailed, it is used to determine from which part of the system the losses originate [6-8].

Some of these studies are: There are some additional studies on shading effect and exergoeconomic analysis; Bayrak et al. [9], in their study, made an experimental setup to create shading at different positions and rates on the photovoltaic panel surface and calculated the efficiency of energy and exergy of the PV system. As a result, they found in the case of horizontal shading a significant loss of the efficiency of energy and exergy of about 99.98%. Bayrak and Öztop [10] investigated the effect of diagonal shading on the performance of PV via energy and exergy efficiency analysis under the same solar radiation. The PV array was left in the natural environment for 30 days for the shading effect of dust accumulation. In their experiment, an artificial shading was created of the triangle-like shape of different shadings. Experimental results showed that the reference panel with the efficiency of highest was only about 0.90% higher than the dusty panel. Variable values were observed for the dynamic shading panel.

It is seen that the energy analysis method is used in experimental and theoretical works on solar power plants and the shading falling on the panel surface and its effects. In addition, when the literature is searched, there is a few scientific research on the dynamic shading on the surface of the PV panel, which occurs in undesirable situations, and only the thermodynamic (exergy) analysis method was used in these studies. Differently, in this study, the exergy and exergoeconomic analysis of the effect of dynamic partial shading on the PV performance caused by an incorrectly positioned structure to the

PV array surface in a solar power plant established in the province Samsun was examined by recording the required data and shading ratio calculations for one consecutive year, 12 months.

2. MATERIALS AND METHODS

In this study, the effects of shading were investigated, starting from the morning until certain hours, caused by the transformer building of a grid-connected power plant capacity of 480 kW in the province of Samsun. You can find detailed technical specifications of the plant in ref. [11].

2.1. PV Array Power Plant

A shading-affected PV string controlled by the inverter (13) and another PV string without shading were selected for reference, inverter (16).

Figure 1. Image of the partially shaded PV array.

2.2. Methods

Sunny and clear days were preferred to get good data from the PV power generation plant. Calculations were made by recording the weather conditions parameters such as the temperature (T_a), the wind speed (v), and the solar radiation intensity (I_s) of the environment where the PV panels were installed.

The area (A) of the shaded PV surface, at 15-minute time intervals starting from sunrise until it left, was recorded with photographs as well as the current, voltage, and power values from the inverter.
Evaluation processes of the effect of dynamic partial shading on PV performance were carried out by exergoeconomic analysis method as follows;

- The instantaneous solar radiation hitting the surface of the PV modules was determined by calculating the Liu and Jordan method [12] and measuring the solar radiation.
- Electrical efficiency calculations of shading-affected and unaffected PV arrays have been discussed in the previous publication [11].
- For economic calculations, instantaneous/average values are used instead of annual electricity generation.

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- Net present value (NPV) is calculated. The operating and maintenance cost of the PV plant is taken as 10% and the salvage value as 5% of the current capital cost (P). The interest rate is taken as 8%.
- The energy loss rate and exergy loss rate of the shaded and un-shaded PV arrays were calculated.
- Related to the previous step the R_{en} and R_{ex} have also been calculated for the shaded and un-shaded PV arrays.

2.3. Analysis of the PV System

In this section, the calculations of energy, exergy, and exergoeconomic analysis, which are the performance and economic parameters of the PV system, shortly will be explained respectively.

2.3.1. Energy analysis

The main energy source of the universe is the sun. Therefore, the radiation of the sun striking the photovoltaic surface will create power named input energy to the PV system which is the basis of the first law of thermodynamics and is expressed as below;

$$P_S = I_S \text{x} A \quad (1)$$

where P_s, I_s and A indicates the sun's radiation power, the intensity of solar radiation, and the area where the sun strikes, respectively.

As it is known, when solar radiation hits the PV panels, the available electricity is converted by the PV device. The maximum current (I_m), voltage (V_m), and power (P_m) equation of the converted useful electricity by the PV array are simply as follows;

$$P_m = I_m \text{x}\, V_m \quad (2)$$

where V_m and I_m express maximum values of voltage and current, respectively.

The evaluation of the energy systems was made by taking into account the principles of the 1st law of thermodynamics, the efficiency and transformation of energy comparison of the PV power plant system were made with the equation given below [13]:

$$\eta = \frac{V_m \cdot I_m}{I_S \cdot A} \quad (3)$$

As understood from the equation, the energy efficiency of a PV system is given as the ratio between the maximum current (I_m) at maximum the power point and the maximum voltage (V_m) value at the maximum power point, and the intensity of solar irradiation (I_S) striking to the surface area (A) of the photovoltaic panel.

2.3.2. Exergy analysis

In thermodynamic (exergy) calculations of a PV power system, it is important to determine the exergy components of the parts that make up the system. The limitations of the Carnot cycle and other thermodynamic parameters such as enthalpy, entropy, and energy conversion, and physical and chemical exergy expressions of a power system have been clarified in the previous discussions [13]. Therefore, these concepts will not be considered in this part of this study. Therefore, electrical and thermal exergy parameters, which are the two main exergy components of this study, will be analyzed [14].

The following equation represents the total exergy balances of PV power systems:

$$\sum Ex_{in} = \sum Ex_{out} + \sum Ex_{loss} + \text{Irreversibility} \quad (4)$$

As it is known, the photovoltaic power system converts the electrical energy or exergy that comes from the sun into useful energy. In more details, detail, exergy analysis of a power system determines to do work, that is, the quality of energy. However, there is always a degradation of some of the energy gained by the power system, in other words, exergy loss. This loss is not recoverable, that is exergy loss also called irreversibility. In order to facilitate the calculations and comparisons, the exergy efficiency of a power system PV module is defined as the ratio of the total output exergy to the total input exergy;

$$\Psi_{PV} = \frac{Ex_{out}}{Ex_{in}} \quad (5)$$

The PV array produces energy or exergy input (Petala's solar exergy model) due to the sun's radiation that strikes the PV surface and is expressed as follows [15]:

$$Ex_{in} = A \cdot I_S(1 - \frac{4}{3}\left(\frac{T_a}{T_S}\right) + \frac{1}{3}\left(\frac{T_a}{T_S}\right)^4) \quad (6)$$

Or

$$Ex_{in} = A \cdot I_S(1 - \left(\frac{\mathrm{T_a}}{\mathrm{T_s}}\right)) \quad (7)$$

Where A shows the surface area of the PV module and T_a and T_s demonstrate ambient and sun temperatures respectively which T_s =5777 K.

The PV modules' exergy output is expressed by [16]:

$$Ex_{out} = Ex_{el} - Ex_{th} \quad (8)$$

As we see from eq. 8, the PV modules' exergy output consists of two basic parameters; heat dissipated to the environment so-called thermal exergy ($E_{x\text{-}th}$), and the useful exergy named electrical exergy ($E_{x,el}$).

When sunlight strikes the PV array it produces useful electricity and it can be expressed as (Note that electrical exergy equals the electrical energy):

$$E_{X,el} = I_m \times V_m \tag{9}$$

Some of the energy coming from the sun causes the upper surface of the PV to heat up. In this case, the surface temperature of the PV panel consisting of cells will increase and thermal energy/exergy losses will occur as waste to the environment, called thermal exergy and its expression is as follows:

$$Ex_{th} = Q(1 - \left(\frac{T_a}{T_c}\right)) \tag{10}$$

Where

$$Q = h_{ca}A(T_c - T_a) \tag{11}$$

And

$$h_{ca} = 5.7 + 3.8v \tag{12}$$

$$T_{cell} = T_a + (T_{NOCT} - 20)\left(\frac{G}{800}\right) \tag{13}$$

Where T_{cell} is the temperature of the cell, the coefficient of the heat transfer is h_{ca}, the velocity of wind is v, and the temperature of the cell operating at nominal T_{NOCT} is usually at about 45 °C.

When equations (9) and (10) are inserted to write the equation of production exergy ($E_{x,out}$) in the exergy balance of the PV array, it can be expressed as follows:

$$E_{x,out} = I_m \cdot V_m - \left(1 - \left(\frac{T_a}{T_c}\right)\right) h_{ca} \cdot A(T_a - T_c) \tag{14}$$

If Equations (7) and (14) are replaced in Eq. (5), the exergy ratio was calculated as:

$$\Psi_{PV} = \frac{I_m V_m - (1-\left(\frac{T_a}{T_c}\right))h_{ca}\, A(T_a - T_c\,)}{AG(1-\left(\frac{T_a}{T_S}\right))} \tag{15}$$

2.3.3. Exergoeconomic analysis

Unfortunately, PV power generating systems, which consist of many components, undergo energy and exergy losses due to different reasons during the power generation process. It is 'exergoeconomic', which is a method of analysis that examines the cost or watt-dollar cost together, which uses the collaboration of economic and thermodynamic analysis together to understand and avoid these unwanted losses. For these reasons, first of all, analyses of energy and exergy main parameters that

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express the quality of the PV power system will be completed, and then after exergoeconomic analysis is done [12].

The exergoeconomic parameter R_{ex} (or R_{en}) is the ratio of exergy loss per annual cost to minimize exergy loss. The exergoeconomic analysis is done together with exergy and economic analysis methods. As a result, cost and exergy disciplines should be discussed together to perform the optimum design of energy-generating systems. According to the generally known definition, according to the first law of thermodynamics, energy as in nature, that is, a change from one form to another, but it cannot be created or destroyed. By contrast, exergy, which is the expression of the second law of thermodynamics, will be exhausted in any action due to irreversibility and is therefore subject to a nonconservative law. For these reasons, the general equilibrium equation can be written as [14];

$$E_{acc} = E_{in} - E_{out} \tag{16}$$

$$E_{x,acc} = E_{x,in} - E_{x,out} - E_{x,cons} \tag{17}$$

The output terms can be rewritten as

$$E_{out} = E_{in} - E_{acc} \tag{18}$$

$$E_{x,out} = E_{x,in} - E_{x,cons} - E_{x,acc} \tag{19}$$

Where, $E_{x;out}$ is overall exergy gain, $E_{x;cons}$ is exergy consumption, and $E_{x;acc}$ is exergy accumulation. To simplify the calculations, two types of thermodynamic losses (L_{en} and L_{ex}) will be considered. Here, L_{en} and L_{ex} are represented as energy-based loss and exergy-based loss, respectively.
Starting from the energy balance equation of a thermodynamic system, the energy loss ratio (L_{en}) calculations of the shaded and unshaded PV array can be written as follows [14]:

$$L_{en} = \sum_{in} Energy - \sum_{out} Energy \tag{20}$$

$$L_{ex} = \sum_{in} Exergy - \sum_{out} Exergy \tag{21}$$

As in most exergoeconomic studies, inspired by Rosen and Dincer [16], the definition of the exergoeconomic parameter 'R' is loss of energy to exergy ratio. First, the loss of energy rate,

$$R_{en} = \frac{L_{en}}{NPV} \tag{22}$$

For exergy loss rates,

$$R_{ex} = \frac{L_{ex}}{NPV} \tag{23}$$

As it is known, there are four common financial analysis methods applied in research on the cost and profitability of PV power systems; net present value (NPV), Profitability Index, Internal Rate of

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Return, and Discounted Payback Period. In this study, NPV, which is one of the four analysis methods, was chosen and can be calculated as follows [16]. Findings and details of net present value (NPV) calculations are made in the 'Conclusions and Discussions' section.

3. RESULTS AND DISCUSSIONS

This section covers the energy, exergy, and exergoeconomic analysis of the adverse effects of shading caused by the power control unit building of a grid-connected PV power plant. This study continued for 12 months, from June 2018 to May 2019. Two equal numbers of PV arrays each controlled by separate inverters, one cleaned and the other not cleaned, were chosen to make controlled experimental observations. To get better results measurements were taken on cloudless and sunny days. Experimental data were recorded and calculations related to the data were made. Technical details of this research are available in the literature [11].

The exergy efficiency of the shaded and un-shaded PV string is discussed in Figures 2-4 correlated to solar irradiation, ambient temperature, and shading ratio parameters versus time. In the exergoeconomic analysis section, 'Operation and Maintenance Costs' and 'NPV Calculations' are given in tables 1 and 2. Then, the changes in the energy (L_{en}) and exergy loss (L_{ex}) ratios and the exergoeconomic parameters R_{en} and R_{ex}, and the shading ratio versus time are presented in figures 5-8.

3.1. Exergy Analysis

As can be seen in Figure 1, analyzes were made depending on the temperature of the environment where the photovoltaic power plant is installed. The ambient temperature for the province of Samsun varies between 9 and 25 degrees Celcius on average during the year.

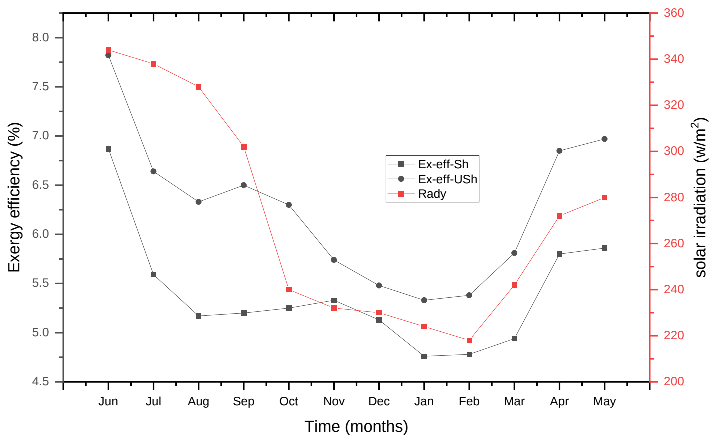

Figure 2. Exergy efficiency (%) and solar irradiation (w/m^2) versus time.

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The correlation of exergy efficiency of the 'Sh-Array' and 'UnSh-Array' PV strings are similar during the 12 months. While the calculated efficiency of exergy values of shaded and unshaded PV arrays was high in the first three months (first, second and third) when the observations started, and an inverse relationship was observed due to the heating of the PV cells due to the ambient temperature and so the increase in thermal loss, on the other hand, a linear relationship was observed in the next months of the year (Fig. 3).

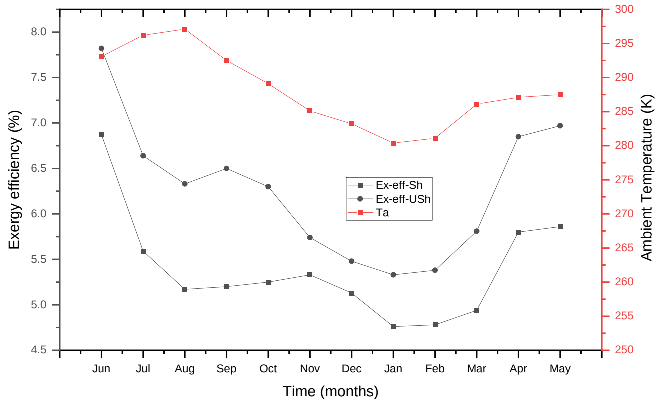

Figure 3. Exergy efficiency (%) and ambient temperature (K) versus time.

On the other hand, the exergy efficiency difference of 'Sh-array' and 'Un-Sh-array' in August, September, and October is about 1.4% maximum. According to these figures, the exergy efficiency of shaded and unshaded PV arrays showed a parallel variation during the 12 months. In terms of exergy efficiency is minimum in January and February in proportion to the ambient temperature and solar radiation, while it is maximum in June (see Figures 2, 3, and 4).

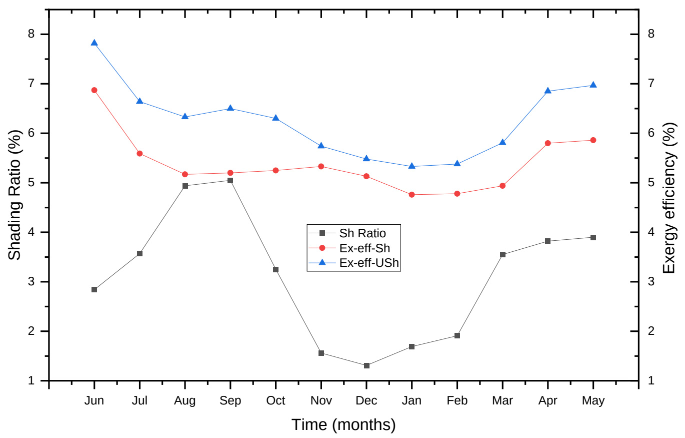

Figure 4. Exergy efficiency (%) and shading ratio (%) versus time.

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In detail, while the exergy efficiency values of 'Sh-string' and 'UnSh-string' were the highest with 6.87% and 7.82%, respectively, in June, they were the lowest at about 4.76% and 5.33% in January. However, depending on the azimuth angle of the incoming solar irradiation, the shading ratio is the lowest at about 1.31% in December. In June, it is only about 2.84%, the highest is about 5.05% in September. According to the graphical analysis data, we can generalize that the exergy efficiency of shaded and non-shaded photovoltaic strings increases positively depending on the power source the sun's rays angle of hitting the PV surface, and the sunshine hours, see Figures 2, 3, and 4.

3.2. Exergoeconomic Analysis

Here, the results data of the exergoeconomic analysis of the impact of dynamic shading created by an undesired structure on the shaded and unshaded PV strings are discussed. Basic components for exergoeconomic analysis; L_{en}, L_{ex}, R_{en}, R_{ex}, and NPV were defined, and calculations and comparisons were made. The data necessary to make the calculations and comparisons were collected from the start of the experiment in June 2018 for 12 months.

Since the grid-connected PV power plant was established as part of an EU support program, estimated values were used to calculate the cost of the system's components. These i.e. 'Cost of capital', modules, stands, etc. design and construction, testing the functioning of the system's components, training of employees-technicians, and operating (maintenance) of the PV power system.

The costs of the components are given in Table1 and 2. The inverter (ABB array) is about $3900 and the cleaning and maintenance cost is about $1000, 25 years 5*5000$(25000$). The discount rate i, which includes inflation and interest rates, is assumed to be 10% on average. Finally, the NPV will be around $100000.

Table 1. Operational and Maintenance Costs.

ABB inverter	2*34 kWe	3900 $
Cleaning and Maintenance cost	5 years	1000 $
Life cycle (25 years)		5*5000 25000$

Table 2. Calculations of the NPV of PV string system.

PV Module (95$)	240*100	24000 $
Support structure ($)	25*240	6000 $
Installation cost	2	5000 $
Capital cost		35000 $
Discount Rate (%)		10
Operational Cost for Each Year ($)		1000 $
NPV		100000 $

In addition, in the calculations of the cost of the PV arrays, the PV modules and the stands, and all the other equipment used for the installation are included. Table 2 shows the costs of all major equipment of the PV system. To find $L_{en;loss}$, the difference between $E_{en,input}$, and $E_{en,output}$ is calculated. Similarly,

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(since L_{ex}=E_{ex}) the exergy loss rate is calculated. Monthly variations in exergoeconomic parameters including R_{en} and $R_{ex;loss}$ are given in Figures 7 and 8. Losses of shaded and non-shaded PV strings peak in June, and then proportionally with T_a and I_s is lowest in December till February and increase again for the next months.

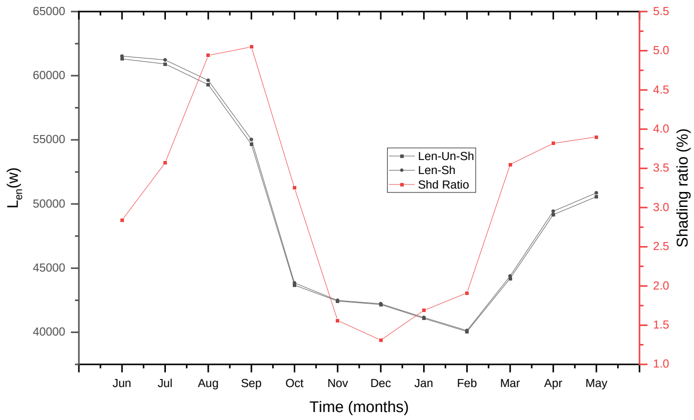

Figure 5. Variations of energy loss rates (L_{en}) and shading ratio versus time.

The energy loss rate of 'Un-Sh-Array' and 'Sh-Array' PV arrays is about 61308 w and 61529 w in June, while the lowest is about 40059 w and 40139 w in February. The variation of 'Un-Sh-Array' and 'Sh-Array' PV arrays examined varying in time (months), it can be seen that the thermodynamic loss rates vary between 55677 and 55524 W in the first month, June, and between 36761 and 36683 W, the lowest in February, the ninth month, see Fig. 5. It can be seen that the graphs of shaded and unshaded PV panels show similar characteristics, and the values of shaded PV arrays are smaller than those of unshaded ones. It can be said that the highest loss rates, starting in June and decreasing due to solar radiation, are the lowest in February, then increase again and shows seasonal characteristics. Details can be seen in figures 5 and 6.

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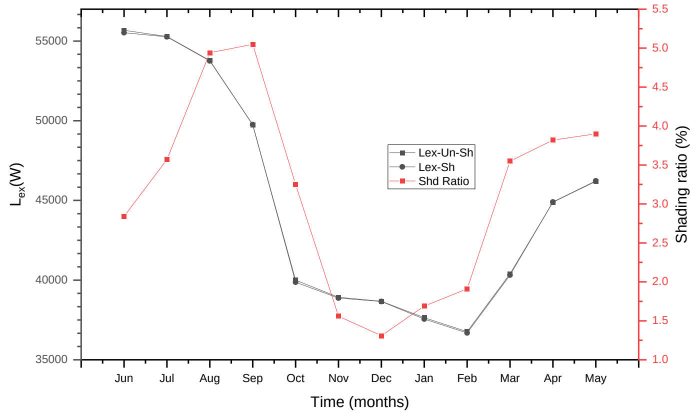

Figure 6. Variations of exergy loss rates and shading ratio versus time.

The correlations of R_{en} and R_{ex} and the shading ratio depending on time can be seen in Figures 7 and 8. R_{en} and R_{ex} values, which are exergoeconomic parameters of shaded and unshaded PV arrays, vary seasonally, depending on the months, that is on the ambient temperature and the angle of incidence of solar radiation. There is a small difference between them. Experimental observations starting from June, as the R_{en} (R_{ex}) values of the PV arrays, it is obvious that the values of the two PV strings (inv. 13 and 16) are at peak in proportion to the intensity of solar irradiation. Then, it starts to decrease slightly until December and is lowest up to February.

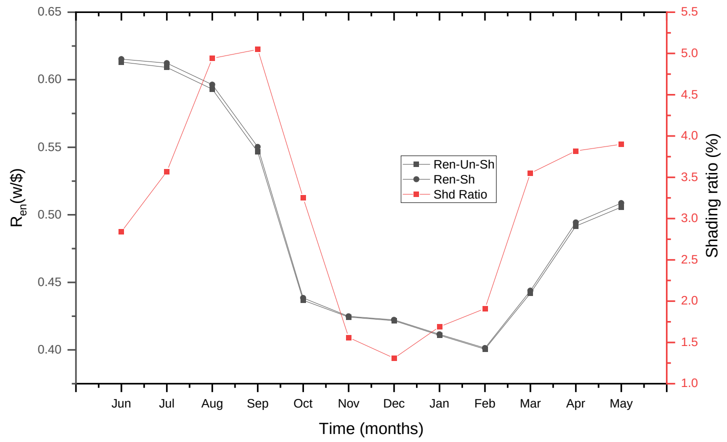

Figure 7. Variations of exergoeconomic parameter (R_{en}) and shading ratio versus time.

In details, R_{en} (R_{ex}) loss values for June were 0.615 (0.555) W/$ for the 'Sh' PV string and 0.613 (0.557) W/$ for the 'Un-Sh' string, then linearly it decreases to 0.401 (0.368) W/$ and 0.401 (0.367) W/$, respectively. In March it slightly increases linearly up to June.

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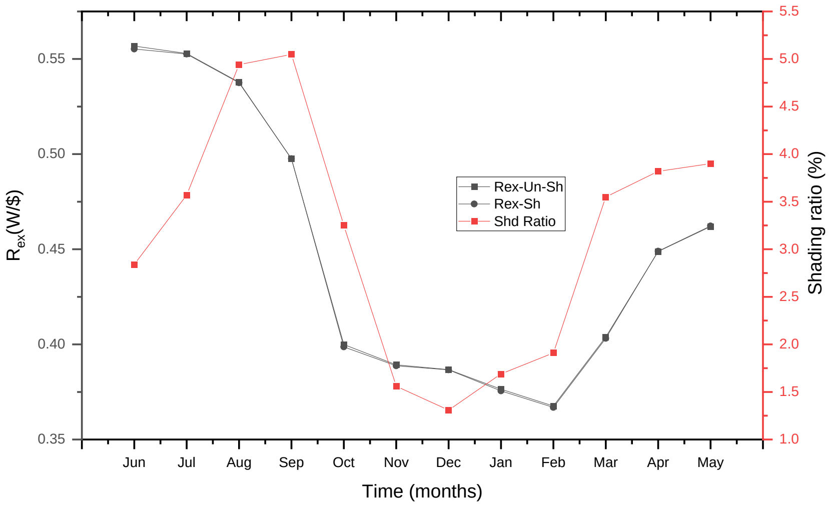

Figure 8. Variations of exergoeconomic parameter (R_{ex}) and shading ratio versus time.

As seen in Fig. 8, there is an increase and decrease observed of the exergoeconomic parameters, R_{en} (R_{ex}), of shaded and unshaded PV arrays in parallel with the solar radiation intensity, but it exhibits a more stable behavior for the T_a parameter of the environment where the PV system is installed. In other words, while the ambient temperature increases from June to the end of August, R_{en} (R_{ex}) values tend to decrease in reverse.

4. CONCLUSIONS

In this study, a comparative analysis was made on the impact of shading on a part of the front surface of a PV string, which was built without considering the angle of incidence of the sun's rays. The shading-affected PV string is controlled by the inverter (13) and the unaffected is controlled by the inverter (16), the observations continued from sunrise to the hours when the shading leaves. Findings and calculations were carried out with exergoeconomic parameters from June 2018 to May 2019. The measurements were conducted on cloudless and sunny days. These scientific observations are based on controlled experimental calculations and their findings can be briefly outlined as follows:

- For both shaded and unshaded PV strings, the meteorological and ecological details such as ambient temperature, sun's irradiation, and speed of the wind are the main factors that affect the production of the PV power plant.
- Since the high T_a causes the PV panels to heat up, there will be losses for both PV strings.
- The intensity of the sun's rays will affect it positively, but after a certain intensity, the value will affect it negatively.
- Positive contributions were observed when wind speed cooled the PV panel.

- As the dynamic partial shading ratio increases (the electric generating area of the panel surface will decrease), the electrical energy and exergy efficiency produced by the affected PV array decrease inversely compared to the unaffected.
- The energy (L_{en}) and exergy (L_{ex}) loss rate decrease slightly as the shading ratio increases.
- The exergoeconomic parameters R_{en}(R_{ex}) are maximum in June 0.615 (0.555) W/$ of the 'Sh' PV string and 0.613 (0.557) W/$ of the 'UnSh' string, then linearly it decreases to 0.401 (0.368)W/$ and 0.401 (0.367) W/$, respectively.
- The shading ratio is a maximum in September of about 5.05% and a minimum of about 1.31% in December, and R_{en} (R_{ex}) is about 0.550 (0.498) W/$.

At the end of 12-month observations a year, undesirable structures built close to the PV arrays can create partial shading, and as a consequence, bad results can occur in electricity generation and cost problems in long service life. It was concluded that there may be a risk of damaging PV modules by creating hot spots on PV cells exposed to long-term undesirable shading. One of the results of this study is that the environmental factors of the structures that make up the PV power systems should be taken into account and it is important to manage the design phase correctly.

ACKNOWLEDGMENT

This scientific research did not receive any special assistance or support from any public or private institution, commercial enterprise, or financial institution in non-profit sectors.

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NOMENCLATURE

PV	:	Photovoltaic
R_{ex}	:	Exergoeconomic parameter, exergetic loss ratio
R_{en}	:	Exergoeconomic parameter, energetic loss ratio

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E_{ex}	:	Exergy
E	:	Energy
T_a	:	ambient temperature
V	:	wind speed
I_S	:	solar radiation intensity
A	:	Area of the PV panels (m^2)
NPV	:	Net present value
I	:	Current
V	:	Voltage
P	:	Power

Greek letters

η_{pce}	:	efficiency
Ψ	:	Exergy efficiency