

1-1-2013

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İZGİ, ERCAN and AKKAYA, YUNUS EMRE (2013) "Exergoeconomic analysis of a solar photovoltaic system in İstanbul, Turkey," *Turkish Journal of Electrical Engineering and Computer Sciences*: Vol. 21: No. 2, Article 4. <https://doi.org/10.3906/elk-1108-25>

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Exergoeconomic analysis of a solar photovoltaic system in İstanbul, Turkey

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Received: 10.08.2011 • Accepted: 08.01.2012 • Published Online: 22.03.2013 • Printed: 22.04.2013

Abstract: This paper deals with the exergoeconomic analysis of a 750-W_p solar photovoltaic (PV) system that is constructed at the Meteorology Park of İstanbul Technical University (41.102° N, 29.02° E) in İstanbul, Turkey. It is known that seasonal differences cause a variation in the exergoeconomic parameters (energy and exergy loss rates) of solar PV systems. Due to this perspective, for regional climatic parameters 2 months are selected: April to represent the spring and August to represent the summer. Within this research, first the exergy analysis is performed on the system and then the economic values of the results are evaluated using the exergy, cost, energy, and mass (EXCEM) method. The energy efficiency of the considered system in August and April varies between 4.5% and 7.3% and 5.5% and 8.5%, respectively. Additionally, the exergy efficiency of the system in August and April varies between 3% and 5.3% and 3.8% and 6.5%, respectively. The average unit cost of the exergy values for August and April are calculated based on the EXCEM model as 0.214 W/\$ and 0.129 W/\$. Moreover, the average unit cost of the energy values for August and April are estimated as 0.222 W/\$ and 0.134 W/\$, respectively.

Key words: Photovoltaic system, solar energy, exergy, exergoeconomic, solar irradiation

1. Introduction

Because of the increasing energy demand all over the world, countries have to improve their installed electricity capacity. Both environmental problems (global warming, air pollution) and the risk of fossil fuel sources coming to an end make renewable energy power plants more important than the others. Moreover, solar photovoltaic (PV) and wind energy systems are preferred more than other renewable systems like wave energy, biomass energy, and tide energy. On the other hand, although solar irradiation and wind velocity are clean energy sources, they do not persist continually for long durations at a given location. Thus, electricity generation that is based on fossil fuels must supplement PV and wind energy systems.

Exergy analysis allows for investigating and designing a system from a thermodynamic point of view, but it is also necessary for the economic values of the results to be considered. Exergoeconomics (also called thermoeconomics by some researchers), as reported in [1], combines these 2 principles (thermodynamic and economic optimization) and allows for more realistic modeling, evaluation, and planning for complex thermal systems such as power plants and heat pump systems [2].

Exergoeconomic analysis was applied by a number of researchers [3–10] to various systems, including power plants, cogeneration systems, heat pump systems, and geothermal district heating systems, because

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it is thought that exergoeconomic analysis is one of the best suitable methods for the design, analysis, and performance improvement studies of energy conversion systems.

In [3], exergoeconomic analysis was studied in relation to a geothermal district heating system (GDHS) for building applications. The study provided insights into the relations between energetic and exergetic losses and capital costs for GDHSs. In [4], a study relating to exergoeconomic analysis was performed by Tsatsaronis and Winhold for energy conversion plants. Additionally, there have been several studies about thermodynamics and exergy applications, such as thermal plant design and optimization [11–13].

The main purpose of this paper is to evaluate the economic properties of a PV system under the climatic conditions of İstanbul, Turkey, based on exergy rules. Moreover, energy and exergy efficiencies of the solar PV system are evaluated and compared for different seasons (spring and summer).

2. System and application

A PV solar power generation and measurement system is constructed at the meteorological park of İstanbul Technical University, in İstanbul, Turkey. This system includes a 750-Wp PV panel (6×125 W/monocrystalline silicon and sun tracking system), thermometers for ambient and PV cell temperature, and pyranometers for global and diffuse solar irradiation measurement devices. There is a 24-V battery system with 200 Ah, regulator, inverter, and generated electricity used for the lighting of the park (Figure 1). The considered area comes under the influence of a mild Mediterranean climate during the summer months and consequently experiences dry and hot spells for about 4–5 months. There is rainfall throughout each year, but comparatively small amounts are measured in the summer months. During the wintertime, this region comes under the influence of the high-pressure system from Siberia and the Balkan Peninsula and the low-pressure system from Iceland. Hence, northeasterly or westerly winds influence the study area with high rainfall amounts, in addition to snow every year with cold and wet spells [14].



Figure 1. The installed PV system.

3. Analysis

It is known that the first law of thermodynamics states the energy conversion rule and the second law also considers energy destruction based on the entropy rule. All thermodynamic rules consider the constant energy

amount for systems, and these do not allow losses and gains in detail except exergy. Thus, PV solar systems have to be examined in detail using exergy rules.

3.1. Energy analysis

In this section, the energy efficiency and energy loss rates of a solar PV system are first taken into account. Depending on the generated electricity, the energy efficiency of the PV system can be written as:

$$\eta = \frac{E_{gen}}{S_t \cdot A}, \quad (1)$$

where E_{gen} is the generated electricity, S_t is the global solar irradiation, and A is the area of the PV. Using the energy balance of a system, the energy loss rate (\dot{L}_{en}) can be identified with the Rosen and Dincer [7,8] approach as:

$$\dot{L}_{en} = \sum_{inputs} \text{Energy flow rates} - \sum_{products} \text{Energy flow rates}. \quad (2)$$

According to Eq. (2), the energy loss rate can be obtained through the following equation:

$$\dot{L}_{en} = S_t \cdot A - E_{gen}. \quad (3)$$

3.2. Exergy analysis

Exergy analysis is a technique that uses conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design, and improvement of energy and other systems. Exergy is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Unlike energy, exergy is not subject to a conservation law (except for ideal, or reversible, processes). Rather, exergy is consumed or destroyed due to the irreversibilities in any real process. The exergy consumption during a process is proportional to the entropy created due to the irreversibilities associated with the process. Exergy is a measure of the quality of energy, which, in any real process, is not conserved, but rather is in part destroyed or lost. Solar PV devices have physical and chemical exergy types.

Physical exergy for PV systems was suggested by Sahin et al. [15] as:

$$E_x = E_{gen} + C_p(T_{cell} - T_{amb}) - T_{amb} \left(C_p \ln\left(\frac{T_{cell}}{T_{amb}}\right) - \frac{Q_{loss}}{T_{cell}} \right). \quad (4)$$

Here, C_p is the specific heat of the silicon, T_{cell} (K) is the cell temperature, T_{amb} (K) is the ambient temperature, and Q_{loss} represents the heat losses from the PV cell.

It is known that enthalpy variation is very important and could be calculated as:

$$\Delta H = C_p(T_{cell} - T_{amb}), \quad (5)$$

where ΔH is the change in enthalpy (J/kg K), T_{cell} (K) is the cell temperature, and T_{amb} (K) is the ambient temperature.

Another important thermodynamic concept is entropy, and this term is calculated with the next equation as:

$$\Delta S = C_p \ln\left(\frac{T_{cell}}{T_{amb}}\right) - \frac{Q_{loss}}{T_{cell}}, \quad (6)$$

where ΔS is the change in entropy (J/kg K) and Q_{loss} represents the heat losses from the PV cell. The heat losses can be represented as:

$$Q_{loss} = C_p(T_{cell} - T_{amb}). \quad (7)$$

For PV systems, electron movements, from a low energy level to a high energy level, depend on the chemical properties of the matter. Generally, in PV applications, silicon is the base matter and the chemical properties of silicon allow to us consider the chemical exergy. The chemical exergy ($\Delta\mu$) of the PV cell can be expressed with the equation given below as:

$$\Delta\mu = (1 - \frac{T_{cell}}{T_p}) [V_{oc}I_{sc} - V_m I_m] \cdot t, \quad (8)$$

where T_p is the sun's temperature, V_{oc} is the PV open circuit voltage, I_{sc} is the short circuit current, V_m is the voltage at maximum power generation, I_m is the current at maximum power generation, and t is the time duration. As given in the next equation, the total exergy of a PV solar cell can be formulated to combine the physical and chemical parts together [10].

$$Ex_{physical} - (I_{sc}V_{oc} - I_m V_m) \frac{T_{cell}}{T_p} \quad (9)$$

It is known that there are 3 main ways to estimate PV solar cell efficiencies, and these are the fill factor and the energy and exergy efficiencies. The first is the fill factor, and it can be defined as follows:

$$\eta_{pce} = \frac{V_m I_m}{S_t}, \quad (10)$$

where V_m is the voltage at maximum power generation, I_m is the current at maximum power generation, and S_t is the global solar irradiation.

Before evaluating the exergy efficiency of a solar PV system, the exergy of the global solar irradiation should be estimated. Solar irradiation has direct and diffuse components that affect the solar PV cell. The magnitude of these components is limited by both Carnot principles and atmospheric conditions. Here, the ambient (T_{amb}) and surface (T_{sun}) temperatures of the sun have a role. Thus, the exergy of the solar irradiance, E_{xsolir} , can be expressed with Eq. (11).

$$E_{xsolir} = S_t (1 - \frac{T_{amb}}{T_{sun}}) \quad (11)$$

Hence, the exergy efficiency (ψ) of PV cell systems can be written as given below:

$$\psi = \frac{E_x}{E_{xsolir}}. \quad (12)$$

In addition, economic analyses in the perspective of exergy unit losses are required. Using the exergy balance of the system, the exergy loss rate (\dot{L}_{ex}) can be identified with Eqs. (11) and (12).

$$\dot{L}_{ex} = \sum_{inputs} \text{Exergy flow rates} - \sum_{products} \text{Exergy flow rates} \quad (13)$$

$$\dot{L}_{ex} = A \cdot S_t (1 - \frac{T_{amb}}{T_{sun}}) - [Ex_{physical} - (I_{sc}V_{oc} - I_m V_m) \frac{T_{cell}}{T_p}] \quad (14)$$

After evaluating the energy loss in Eq. (13) and exergy loss in Eq. (14), the exergoeconomic analysis can be easily investigated using earlier studies [3,7,8]. In the exergoeconomic analysis of PV solar cells, R is used to express the ratio between thermodynamic loss rate L and capital cost K . R can be defined as below:

$$\dot{R} = \frac{\dot{L}}{K}. \tag{15}$$

Eq. (14) is the general form of R . If it is based on the energy loss rate (\dot{R}_{en}) or the exergy loss rate (\dot{R}_{ex}), it will be expressed as follows:

$$\dot{R}_{en} = \frac{\dot{L}_{en}}{K}, \tag{16}$$

$$\dot{R}_{ex} = \frac{\dot{L}_{ex}}{K}. \tag{17}$$

These equations let us consider the exergy parameters together with their economic values. In this research, the results of Eqs. (1), (12), (13), (16), and (17) will be discussed in detail.

4. Results and discussion

In this section, exergy efficiency, energy efficiency, and some exergoeconomic parameters of a 750-Wp solar PV system are given. Additionally, details of this research are given in [16]. As mentioned before, within the study, global solar irradiation, maximum generated power by the system, voltage, current, cell temperature, and ambient temperature are measured.

It can be seen that the generated electricity values proportionally increase with the measured global solar irradiation and a second-degree polynomial relation occurs between these variables. The generated electricity is increased until the global solar irradiation reaches 900 W/m²; after that, the value tends to stay at a constant level in April and as expected, the values in August are observed to be higher than those in April for both variables (Figure 2).

The exergy values of the PV system vary significantly over time and those in August are higher than those in April. While the exergy values in August range between 100 and 200 W, the values of this thermodynamic parameter in April range between 40 and 125 W (Figure 3).

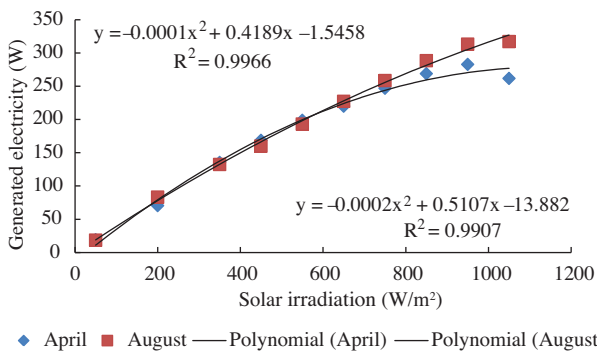


Figure 2. Relation between the generated electricity and global solar irradiation.

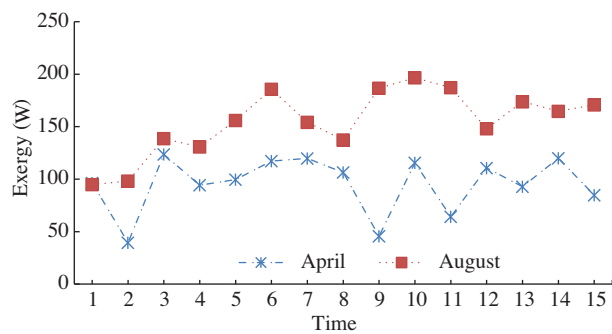


Figure 3. Variation of exergy values of the PV system in April and August.

In Figure 4, it is seen that energy (heat) losses vary significantly over time. It is estimated that the energy losses of the PV system in August are higher than in April. When the August losses are compared with

the April losses, it is seen that like their seasonal characteristics, the losses in August are steadier and higher than those in April. In August, the energy losses reach 2500 W as a minimum value and 4000 W as a maximum value. In April, the energy losses range between 500 and 3500 W.

It can be seen that energy loss rate and global solar irradiation have a linear relationship during August and April (Figure 5). As is seen, these 2 months show similar behaviors depending on the solar irradiation, but considering another effective meteorological variable, ambient temperature, gives meaning to this illustration. Although the solar irradiation in August is higher than in April, the negative effect of the ambient temperature on the PV cell causes a decrease in the electricity generation in August. On the contrary, in April, the solar irradiation potential is lower than in August; the negative effect of temperature on the PV cell in April is lower. Additionally, another important tool for comparing the results is the relative error approach. For R_{en} , the relative error between the 2 months shows differences, especially in the lower and upper parts of the solar irradiation values. The same situation also occurs for the R_{ex} values, as seen in the Table.

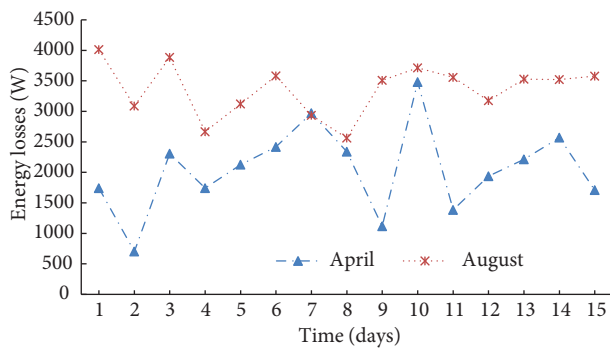


Figure 4. Energy (heat) loss variation over time in April and August.

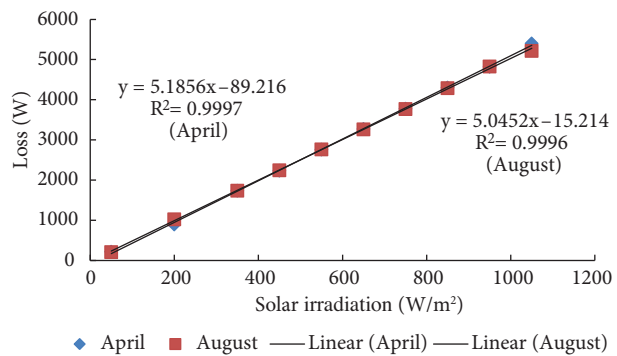


Figure 5. Variation of energy losses with global solar irradiation.

Table. Relative differences between R_{en} and R_{ex} values of April and August depending on the solar irradiation.

Solar irradiation (W/m ²)	R_{en} , relative error (%)	R_{ex} , relative error (%)
50	4.65	3.92
200	12.51	12.74
350	0.02	0.10
450	0.44	0.45
550	0.16	0.14
650	0.29	0.34
750	0.22	0.28
850	0.34	0.43
950	0.15	0.05
1050	3.43	3.61

Exergy losses in the PV system can be seen in Figure 6. Variation of the exergy losses with time is similar to energy losses and, with time, like deviation in energy losses; the system has fewer loss fluctuations in August than in April. In spring, or in other words in April, the variability of the weather conditions is very high, and the results of these oscillations can be seen in Figures 4 and 6.

As with the energy losses, it is seen that the exergy losses have a high linear relation to the global solar irradiation during the considered months (Figure 7).

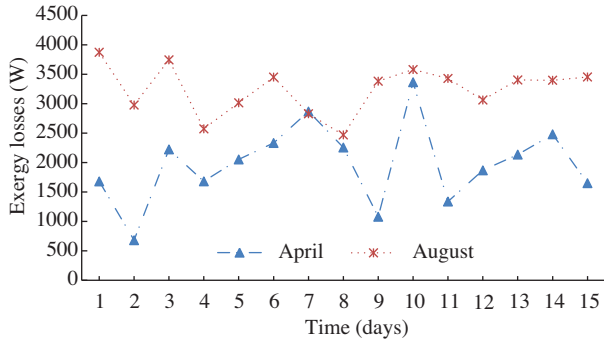


Figure 6. Exergy loss variation over time in April and August.

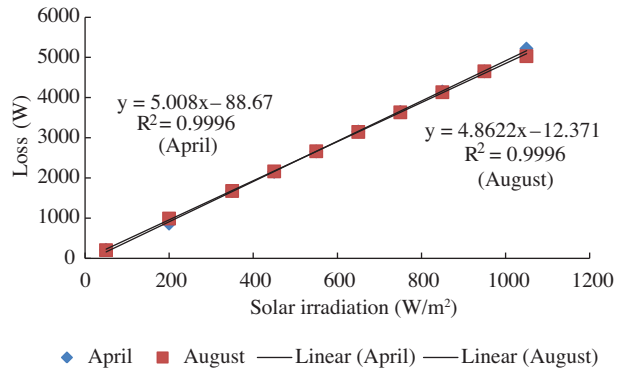


Figure 7. Exergy loss in relation to global solar irradiation.

Additionally, it can be seen that the R_{en} values vary significantly over time (Figure 8). As mentioned before, in the exergoeconomic analysis of PV solar cells, R is used to express a ratio between thermodynamic loss rate L and capital cost K . In this application, when this ratio is considered for energy R_{en} , August has higher and steadier values than April. The average R_{en} values for August and April are 0.222 W/\$ and 0.134 W/\$, respectively. Economically, this means that the losses in August are more valuable than those in April.

The global solar irradiation and R_{en} values have a linear relation for both of the considered months, as seen in Figure 9. The R_{en} values in August and April, as a function of the global solar irradiation, have a high coefficient of determination at 0.9996 and 0.9997, respectively.

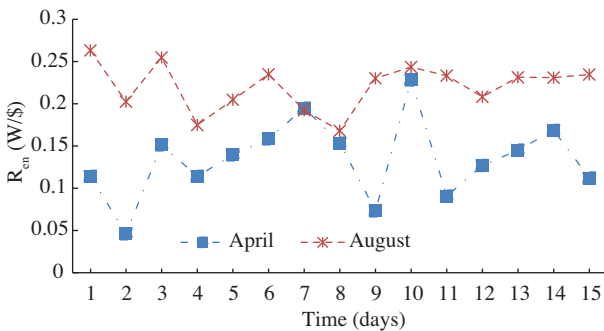


Figure 8. Variation of R_{en} values in April and August.

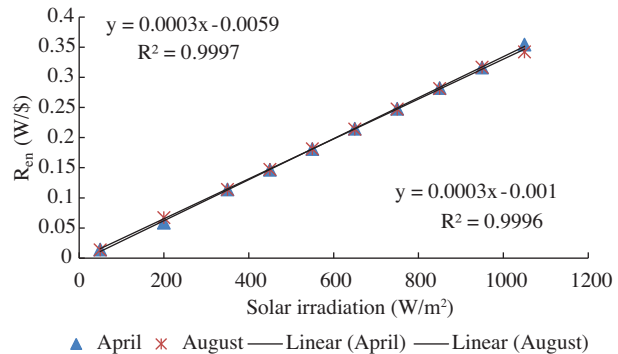


Figure 9. Relation between R_{en} and global solar irradiation.

Just as with the R_{en} , the R_{ex} values also vary significantly over time (Figure 10). While the R_{ex} values range between 0.16 and 0.26 W/\$ in August, they range between 0.04 and 0.23 W/\$ in April. The average R_{ex} values in August and April are 0.214 W/\$ and 0.129 W/\$, respectively.

The relation between the R_{ex} values and the global solar irradiation is shown in Figure 11. The global solar irradiation and R_{ex} values have a linear relation for both August and April.

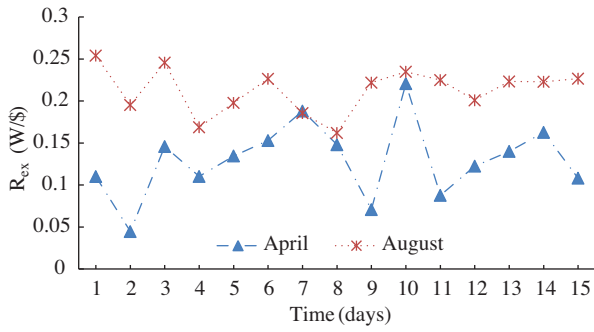


Figure 10. Variation of R_{ex} values in April and August.

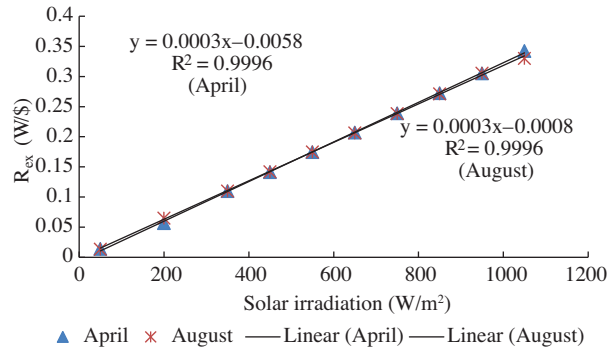


Figure 11. Relation between R_{ex} and global solar irradiation.

The energy and exergy efficiencies of the system are given together in Figure 12, where it is seen that the energy efficiency of the system has higher values than the exergy efficiency for both months. The energy efficiency of the system for August and April varies between 4.5% and 7.3% and 5.5% and 8.5%, respectively. Moreover, the exergy efficiency of the system for the mentioned months varies between 3% and 5.3% and 3.8% and 6.5%, respectively. The average values of the energy and exergy efficiency for August are 6.67% and 4.84%, respectively. Additionally, the average value of the energy efficiency in April is 7.35% and the exergy efficiency for the same month is estimated as 5.37%.

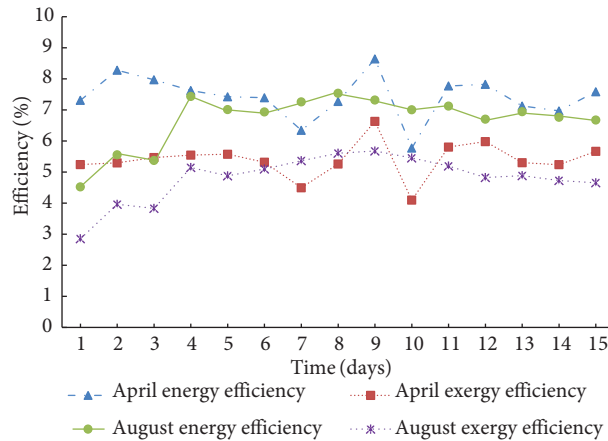


Figure 12. Variation of energy and exergy efficiencies in April and August.

5. Conclusions

In this paper, the exergoeconomic parameters of the energy and exergy efficiencies for a 750-Wp solar PV system were investigated in different months (April and August). This study aimed to determine how a solar PV cell is affected by different weather conditions, and the effects of these situations on economic yields were considered based on exergy rules. Thus, some functions based on global solar irradiation, energy, exergy, and exergoeconomic parameters were evaluated with high correlations. As expected, higher global solar irradiation, which affects the solar PV system, caused high energy and exergy losses in the system. Although the solar irradiation in August is higher than in April, the electricity generation in April is more than in August due to the negative effect of the ambient temperature on the PV cell. On the contrary, in April, this region has a lower

solar irradiation potential than in August, but the negative effect of temperature on the PV cell in April is lower. High relative differences occurred between the R_{en} and R_{ex} values of both considered months with low and high solar irradiation data. In this research, an EXCEM model was applied for exergoeconomic analysis. The EXCEM analysis and its financial parameters allow us to do more realistic modeling and planning for solar PV systems.

In future work, using a wider range of data including all months of the year, exergoeconomic analyses for both wind and solar energy will be considered.

Nomenclature

A	Total area of photovoltaic panel	T_{cell}	Photovoltaic cell temperature
I_{sc}	Short-circuit current	T_{amb}	Air temperature
V_{oc}	Open-circuit voltage	T_p	Sun temperature
C_p	Specific heat of silicon	Ex_{phy}	Physical exergy of photovoltaic cell
S	Entropy	η_{pce}	Power conversion efficiency
Ex	Exergy	S_t	Solar irradiation
η	Energy efficiency	Ex_{solir}	Exergy of solar irradiance
ψ	Exergy efficiency	T_{sun}	Sun temperature
E_{gen}	Generated electricity at highest energy content of the electron	L_{ex}	Exergy loss rate
V_m	Voltage at maximum power generation	L_{en}	Energy loss rate
I_p	Current at maximum power generation	K	Capital cost
H	Enthalpy	R	Ratio of thermodynamic loss rate to capital cost
$\Delta\mu$	Chemical potential difference	\dot{R}_{en}	Ratio of energy loss rate to capital cost
		\dot{R}_{ex}	Ratio of exergy loss rate to capital cost

Acknowledgments

The authors acknowledge the Scientific and Technological Research Council of Turkey (TÜBİTAK) for support under project number 107M331, entitled “Construction of a General Model for Inputs, Outputs, Losses, and Efficiencies of Wind-Solar Hybrid Systems by Spatio-Temporal and Exergy Methods in İstanbul Conditions”.

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