©2016 Published in 4th International Symposium on Innovative Technologies in Engineering and Science 3-5 Nov 2016 (ISITES2016 Alanya -Turkey)

Exergoeconomic Analysis of a Solar Photovoltaic Module in Karabük, Turkey

*Mutlucan BAYAT
*Faculty of Engineering, Department of Mechanical Engineering, Karabuk University, Turkey

Abstract

This paper deals with the exergoeconomic analysis of a 130 Watt-peak (Wp) solar photovoltaic (PV) panel that is constructed at the top of Engineering Faculty of Karabuk University (41.12 N, 32.39 W) in Karabuk province, 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 four days in November are selected. 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 method. The energy efficiency of the considered system in November varies between 9,6% and 17,1%, respectively. Additionally, the exergy efficiency of the system in November varies between 9,2% and 15,8% respectively. The average unit cost of the exergy values for November are calculated based on the model as 0.191 W/$ and 0.392 W/$ which are the minimum and maximum rates, respectively. Moreover, the average unit cost of the energy values for selected days are estimated as 0.175 W/$ and 0.326 W/$, respectively.

Key words: Exergoeconomic analysis, energy, exergy loses, PV module.

1. Introduction

In this advanced technology era, the energy demand has enormously increased day by day. As a result of this, the limited sources of energy have been faced to be consumed very rapidly. Besides, the usage of fossil fuels has risen and this situation has ended up with other environmental concerns, for instance, the emission of greenhouse gases which causes the global warming [1]. Therefore, in order to minimize detrimental impacts on the environment, the utilization of renewable energy sources carries a great importance and provides substantial benefits for power generation.

The solar power is affordable, inexhaustible and clean source of energy. Employing solar energy therefore brings enormous benefits considering enhance sustainability, decrease pollution and limiting global warming. It is not only a powerful option to reduce environmental concerns; it provides also an indigenous solution for diminishing use of fossil fuels and keeping clean power generation prices [2].

Exergy analysis is known by researches and engineers as an essential tool to assess of a PV system's performance with the thermodynamic approach. This analysis does not only

*Corresponding author: Address: Faculty of Engineering, Department of Mechanical Engineering Karabuk University, 78050, Karabuk TURKEY. E-mail address: mutlucanbayat@karabuk.edu.tr, Phone: +903704332021

demonstrate energy utilization efficiency, it provides also various useful results corresponding exergy efficiency, which become a significant principle for comparing of solar PV modules. Therefore, there has been an enormous interest in exergetic calculations, considering irreversibility and energy delivery in the system, and many scientists have conducted theoretical and experimental study on this field, currently [3].

Among analysis methods that have been used to evaluate the performance of a thermal energy system, there is a technique that combines thermodynamic and economic principles. Thermoeconomics is a general term that describes any combination of a thermodynamic analysis with an economic one. Compared with energy, exergy is a more consistent measure of economic value. Exergoeconomics rests on the philosophy that exergy is the only rational basis for assigning monetary costs to a system's interactions with its surroundings and to the sources of thermodynamic inefficiencies within it [4].

In the literature, exergoeconomic analysis of glazed hybrid photovoltaic thermal module air collector has been analyzed by [5]. Exergoeconomic analysis of power plants operating on various fuels has been studied by different authors [6] and they concluded that the results may provide useful insight into the relations between thermodynamics and economics, both in general for electric generating stations, help demonstrate the merits of second-law analysis and extend throughout the electrical utility factor. Exergoeconomic analysis of a solar assisted ground source heat pump greenhouse heating system has been presented by scientists [7] and they explained the simple thermoeconomic optimization methodologies to determine a correct design of new equipment. Exergoeconomic analysis of various thermal systems has been discussed by [8]. Reference [9] have presented an exergoeconomic study of geothermal district heating systems through mass, energy, exergy and cost accounting and a case study for the Salihli geothermal district heating system (SGDHS) in Turkey to illustrate the present method. Reference [10] also presented an application of an exergoeconomic model, through exergy and cost accounting analyses, to the Gonen geothermal district heating system (GDHS) in Balikesir, Turkey for the entire system and its components and they found that an increase of the load condition leads to a decrease in the overall thermal costs, which will result in more cost- effective energy systems for buildings.

2. System Description

In this experimental study, a silicon based polycrystalline solar PV module was performed throughout November in Karabuk province in Turkey. In order to carry out exergoeconomic analysis, a PV system was installed on the top of the Engineering Faculty, Karabuk University, Karabuk, Turkey. There are 72 polycrystalline PV modules as seen in Fig. 1. Each module has 0.67 m × 1.5 m dimensions and also has a rated power output of 130 Watt-peak (Wp) with a rated voltage of 21,9 V. The other specific features of each PV module have been given in Table 1. Here, the module properties have been presented in standard test conditions including 1000 W/m2 global solar radiation, 1,5 AM and 25 ^{o}C ambient temperature.

To perform analysis, measurements on a PV module have been carried out between 9 am to 17 pm in a 30 minute intervals during November. For defining and evaluating energy efficiency rates, electrical parameters of the module e.g. nominal current-voltage, open circuit voltage and short-circuit current have been measured. Besides, atmospheric parameters such as global solar radiation, the ambient and panel temperature as well as wind speed have been recorded since environmental conditions affect the real working performance the module.

For measuring parameters mentioned above, some instruments have been utilized. For instance, the panel backside temperature measurement is performed with the calibrated digital thermocouple and thus, the temperature data has been provided to be taken in the middle of the module. Delta OHM HD2303 coded a digital anemometer is used to measure the ambient temperature and also the air flow on the just top of the PV surface. The global solar radiation has been measured by using a MS-410 coded pyranometer.

For obtaining current-voltage parameters, a wire-wound rheostat which has 50 Ω resistance capacity was used. In order to define open circuit voltage (Voc) and short-circuit current (Isc), two points on the rheostat where low resistance and high resistance are located have been used. For also defining maximum current and voltage, UNI-T UT61B and MY-68 coded two digital multimeters were utilized. All current-voltage data read by multimeters have been recorded into an excel sheet and maximum power points (Pmax) have been selected for each half an hour by multiplying read the values. The components of the values indicating maximum power points were considered as the maximum voltage (Vmax) and the maximum current (Imax). Fig. 2 shows some measurement devices used in this experimental study.

Using these instruments, the data on the parameters has been collected on the selected days and in order to better obtain changes in exergoecomic values, four days have been selected. Considering the obtained data, exergy analysis has been performed at first, and then exergoeconomic parameter results have been interpreted on the selected days.

Fig.1: The installed PV system

Tab. 1: The panel properties within standard test conditions

IBC PolySol 130 GC		Technical Data
Nominal peak power	W_p	130.0
Nominal voltage	V	18.0
Nominal current	A	7.23
Open circuit voltage	V	21.9
Short-circuit current	A	7.9
Temperature coefficient of I_{sc}	%/K	+0.05
Temperature coefficient of V_{OC}	mV/K	-78.8
Temperature coefficient of P_{max}	%/K	-0.46
Power conversion efficiency	%	12.94
Power Tolerance	%	±2.5
Fill Factor (FF)	-	75.22
Number of cell	-	36
Length	mm	1500
Width	mm	670
Height	mm	42
Weight	kg	12.0
Effective Area	m^2	0.8649

Fig. 2: Some measurement instruments used in experiment

3. Exergy Analysis

All the exergy efficiency calculation methods based on the fundamental efficiency expression depending on the ratio of input and output parameters in any system. For point of view, the exergy efficiency of a PV system can, in general, be given as

$$\psi = \frac{\dot{E}x_{output}}{\dot{E}x_{input}} = \frac{\dot{E}x_{PV}}{\dot{E}x_{solar}} \quad (1)$$

where $\dot{E}x_{PV}$ is the total exergy rate of the PV which is mainly electrical power output of the system considering exergy destruction. Thus, exergy of electrical energy can be defined as [11]

$$\dot{E}x_{electrical} = V_{max} I_{max} \quad (2)$$

where V_{max} and I_{max} represent the voltage and current at the maximum power operation point, respectively.

For $\dot{E}x_{PV}$ calculation process, thermal exergy occurring due to the thermal energy gained by the system during electricity generation is also considered. The thermal exergy of the system $\dot{E}x_{\text{thermal}}$, consists of heat loss from the PV surface to the ambient and can be given as [12]

$$\dot{E}x_{thermal} = \left(1 - \frac{T_{ambient}}{T_{cell}}\right) \dot{Q} \quad (3)$$

Here, T_{ambient} refers to the ambient temperature and T_{cell} denotes the temperature of solar cell. $\dot{Q}$ also represents the available thermal energy (W) and can be defined as

$$\dot{Q} = h_{ca} A (T_{cell} - T_{ambient}) \quad (4)$$

where A(m^2) represents the effective area of PV surface. h_{ca} (W/m^{2}K) also refers to the convective and radiative heat transfer coefficient from the cell to the ambient. It can be calculated by considering wind velocity (υ), density of air and the surrounding (ambient) conditions given by following equation [13]

$$h_{ca} = 5{,}7 + 3{,}8.\upsilon \quad (5)$$

Here, it should be addressed that thermal part is subtracted from electrical exergy rate while calculating total exergy of a PV, since the thermal energy gained by the system is not desirable in the case of the PV. Hence, $\dot{E}x_{PV}$ can be derived considering both electrical and thermal exergy expressions (1-5) given by

$$\dot{E}x_{PV} = \dot{E}x_{electrical} - \dot{E}x_{thermal} \quad (6)$$

And then, it becomes

$$\dot{E}x_{PV} = V_{max}I_{max} - \left(1 - \frac{T_{amb.}}{T_{cell}}\right)[h_{ca}A(T_{cell} - T_{amb})] \quad (7)$$

For evaluating the exergy efficiency of solar cells, total solar irradiation is also needed. The incident solar radiation with the direct and diffuse components received on the PV surface affects the current and power output of the PV module. With this approach, the exergy of solar irradiation, $\dot{E}x_{solar}$ (also known as $\dot{E}x_{input}$), depends on the intensity of solar irradiance and the area of the PV surface given as [14]

$$\dot{E}x_{solar} = \left(1 - \frac{T_{amb.}}{T_{sun}}\right)S_T A \quad (8)$$

Here, S_T (W/m^2) defines the hourly measured global solar irradiance. T_{sun} denotes the effective temperature of the Sun and can be taken as 5777 K as in Holmberg's study [15].

In order to obtain the final exergy efficiency expression for a PV system according to Reference [16], Eqs. (7) and (8) are substituted into Eq. (1) given as

$$\psi_{PV} = \frac{V_{max}I_{max} - \left(1 - \frac{T_{amb.}}{T_{cell}}\right)[h_{ca}A(T_{cell} - T_{amb.})]}{\left(1 - \frac{T_{amb.}}{T_{sun}}\right)S_T A} \quad (9)$$

4. Exergoeconomic Analysis

Exergoeconomic analysis uses economy and energy-exergy analyses together and defines systems' real product costs. In this study, Exergy Cost Energy Mass analysis, which is proposed by Rosen and Dincer [17] is used and this analysis includes two parts. First, all energy and exergy analyses are performed. Then, the system is assessed from the exergoeconomic point of view. According to conservation and conversation of energy law, mass and energy are conserved during the process. Also, exergy is destructed during the process. As a result, mass, energy and exergy equations can be written as follows:

$$\dot{m}_{in} - \dot{m}_{out} = \dot{m}_{acc} \quad (10)$$
$$\dot{E}n_{in} - \dot{E}n_{out} - \dot{E}n_{loss} = \dot{E}n_{acc} \quad (11)$$
$$\dot{E}x_{in} - \dot{E}x_{out} - \dot{E}x_{loss} - \dot{E}x_{dest} = \dot{E}x_{acc} \quad (12)$$

where "m" is mass, "En" is energy and "Ex" is exergy. Also, subscripts "in" is input, "out" is output, "acc" is accumulated, "loss" is loss and "dest" is destruction.

There are generally two losses as energy loss ($\dot{E}n_{loss}$) and exergy loss ($\dot{E}x_{loss}$) in a process. Also, exergetic point of view, exergy destruction ($\dot{E}x_{dest}$) can be occurred. Energy loss rate is shown as "$\dot{L}_{en(loss)}$" in the exergoeconomic analyses. Furthermore, exergy loss and destruction rates are illustrated as "$\dot{L}_{ex(loss)}$" and "$\dot{L}_{en(dest)}$", respectively. The total of the exergy loss and destruction rates is stated as "$\dot{L}_{ex(tot)}$".

$$\dot{L}_{en(loss)} = \dot{E}n_{loss} \quad (13)$$

$\dot{L}_{ex(loss)} = \dot{E}x_{loss}$ (14)
$\dot{L}_{ex(dest)} = \dot{E}x_{dest}$ (15)
$\dot{L}_{ex(tot)} = \dot{E}x_{loss} + \dot{E}x_{tot}$ (16)

In this analysis, exergoeconomic parameter ($\dot{R}$) is developed. When the energetic terms are considered, this parameter is shown as "$\dot{R}_{en(loss)}$". If the exergetic terms are taken into account, exergoeconomic parameter is stated as "$\dot{R}_{ex(loss)}$", "$\dot{R}_{en(dest)}$", "$\dot{R}_{ex(tot)}$". Here, the exergoeconomic parameter ($\dot{R}$) is a ratio of thermodynamic loss rate ($\dot{L}$) to capital cost of the equipment (K_i) [18].

$$\dot{R} = \frac{\dot{L}}{K_i} \quad (17)$$

If the energy loss rates are considered, exergoeconomic parameter ($\dot{R}_{en(loss)}$) is defined by

$$\dot{R}_{en(loss)} = \frac{\dot{L}_{en(loss)}}{K_i} \quad (18)$$

If the exergetic parameters (exergy loss and destruction) are taken into account, exergoeconomic parameters are calculated as follows:

$$\dot{R}_{ex(loss)} = \frac{\dot{L}_{ex(loss)}}{K_i} \quad (19)$$
$$\dot{R}_{ex(dest)} = \frac{\dot{L}_{ex(dest)}}{K_i} \quad (20)$$
$$\dot{R}_{ex(tot)} = \dot{R}_{ex(loss)} + \dot{R}_{ex(dest)} = \frac{\dot{L}_{ex(loss)} + \dot{L}_{ex(dest)}}{K_i} \quad (21)$$

5. Results And Discussion

Exergoeconomic analyses has been performed during November by collecting data on the specific parameters using some instruments mentioned in Section II. In order to better obtain changes, 4 days have been selected and analysis results have been illustrated on following figures. According to these figures, maximum power points, energy and exergy loss rates have showed a parallel variation during the month. Going further in details, P_{max} values have taken a place between 10,3 W and 78,2 W as the minimum and maximum rates in the 1st and 20th of November, respectively. Energy loss rate have changed between 46,3 W and 420,8 W in the 1st and 20th of November, respectively. Similarly, exergy loss rates have been 77,4 W and 524,1 W in the same days. For exergoeconomic parameters, in contrast, it is seen that R_{en} values differ from 0,172 (W/$) to 0,398 (W/$) as the minimum and maximum rates in the 20th and 30th of November, respectively. Among R_{ex} values on selected days, the minimum has been observed in 20th of November with 0,191 (W/$) rate, the maximum also has been seen in 30th of November with 0,4 (W/$) rate. In general, depending on the L_{en} and L_{ex}, R values have decreased during the midday (the minimum is at around 12:30) and increased during evening (the maximum is at 17:00).

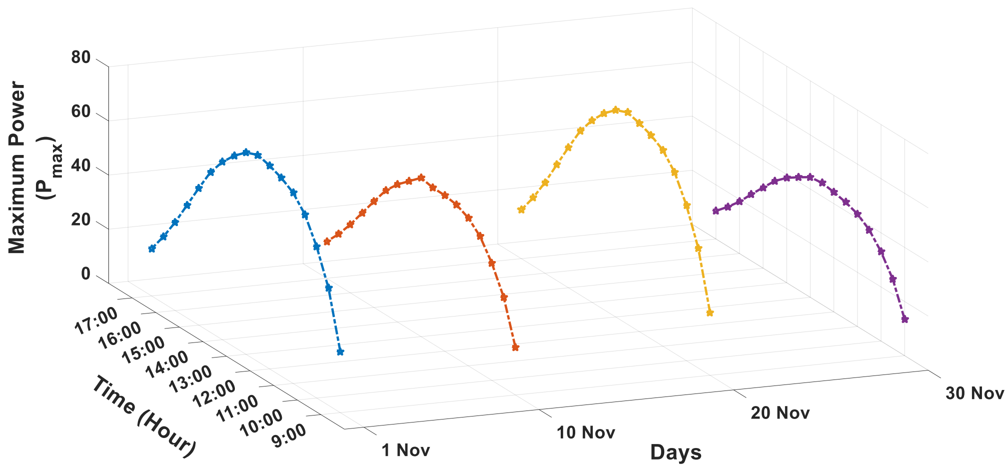

Fig. 3: The variation of maximum power point on selected days

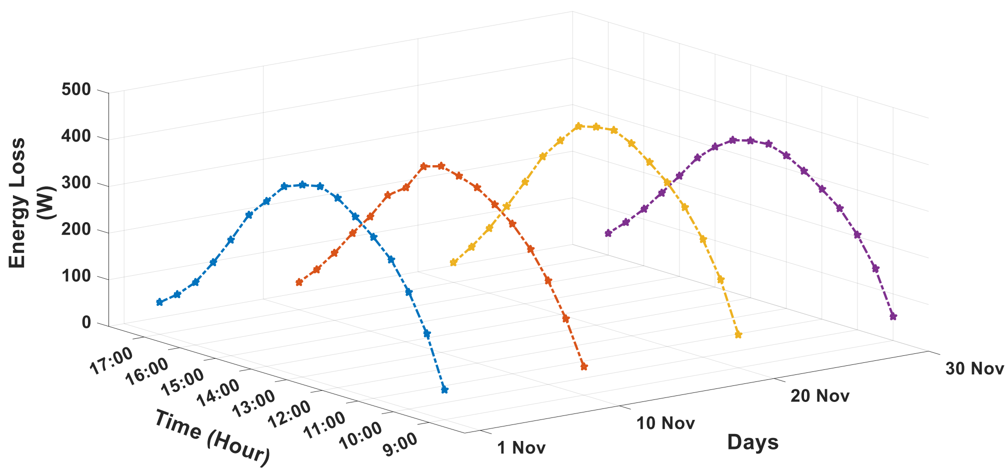

Fig. 4: The variation of energy loss rate on selected days

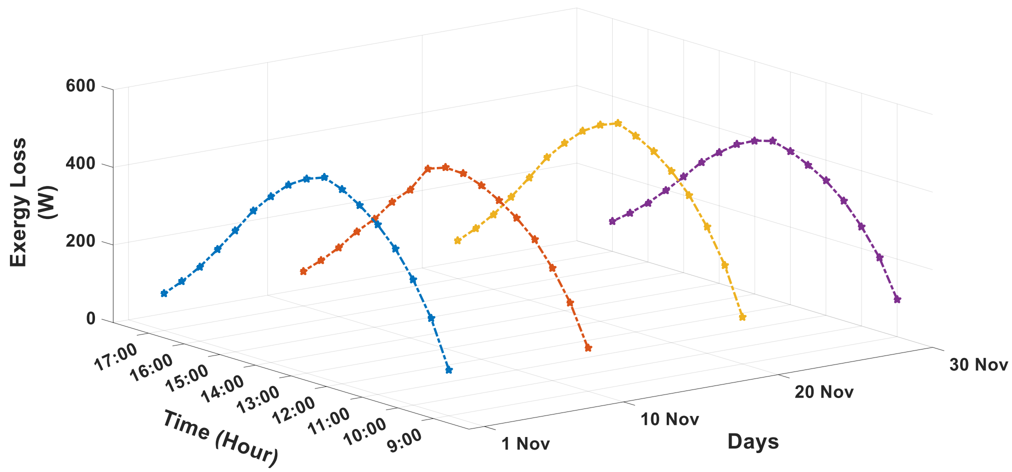

Fig. 5: The variation of exergy loss rate on selected days

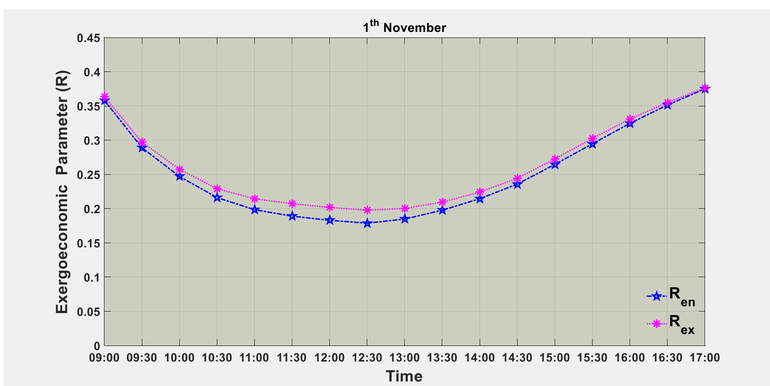

Fig. 6: The variation of exergoeconomic parameters on 1st November

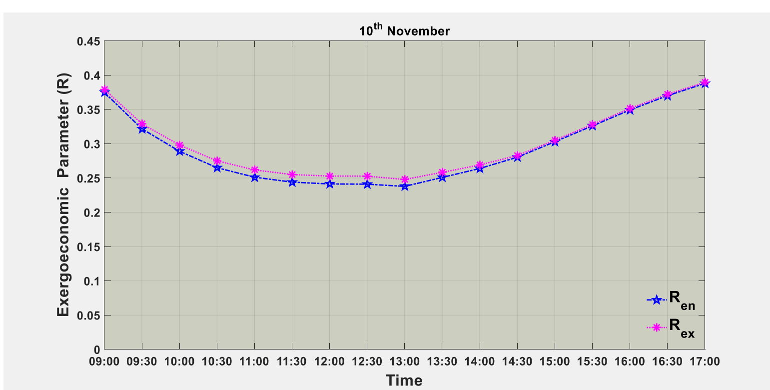

Fig. 7: The variation of exergoeconomic parameters on 10th November

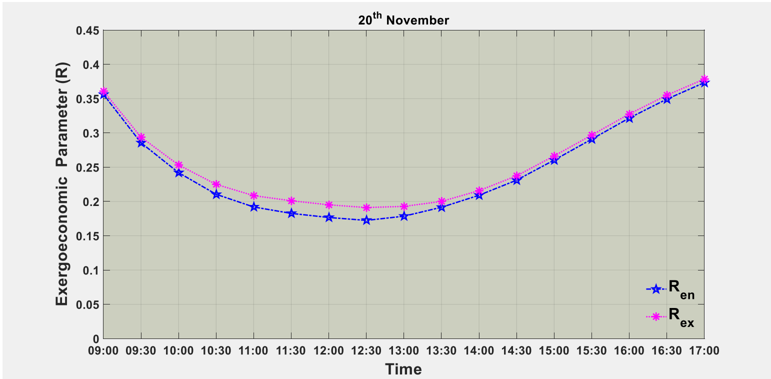

Fig. 8: The variation of exergoeconomic parameters on 20th November

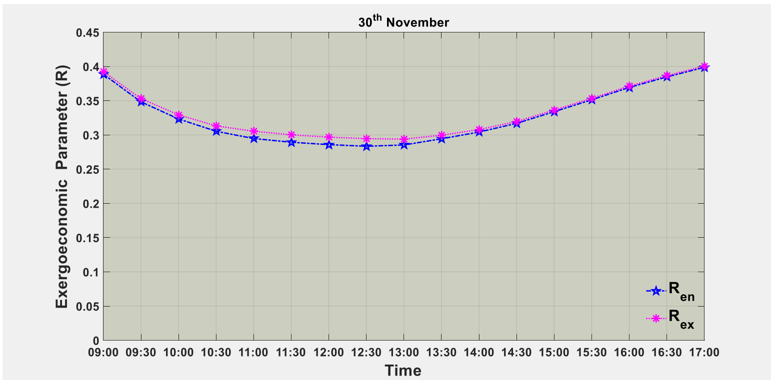

Fig. 9: The variation of exergoeconomic parameters on 30th November

6. Conclusion

A case study has been presented with exergoeconomic perspective which provides loss and destruction cost information. It is seen that electrical parameters of the PV module have been influenced by environmental conditions. Therefore, maximum power output and energy-exergy loses have changed throughout November. However, it can be said that exergoeconomic parameters in (W/$) have increased in general as being the ratio of the exergy loss to the capital cost, R_{ex} values are higher than R_{en} which means exergetic loses are bigger than energy loses. Thanks to the obtained data during the study, it is observed that R_{ex} is the key parameter of exergoeconomic analysis of energy systems. Also it is believed that for any technology there is an appropriate value for R_{ex} where the design of the device is more successful if the R_{ex} for that device approaches that appropriate value. Finally, it is estimated that mature technologies have achieved a balance of exergy loss and capital cost over the time that is appropriate to the circumstances.

Acknowledgment

This proceeding paper is based on the experimental study supported by Karabuk University Scientific Research Project Coordinator (BAP) with the project number KBU-BAP-16/1-YD-038.

References

[1] J. H. Yuan, J. G. Kang, C. H. Zhao, and Z. G. Hu, "Energy consumption and economic growth: Evidence from China at both aggregated and disaggregated levels," *Energy Econ.*, vol. 30, no. 6, pp. 3077–3094, 2008.

[2] J. Luther, "World in transition – towards a sustainable energy system," *Ger. Advis. Counc. Glob. Chang.*, p. 3, 2013.

[3] M. Özalp, M., Bayat, "A comparative and experimental study on different exergetic efficienciy methods of a solar panel," no. 1980, 2016.

[4] R. Rayegan, "Exergoeconomic Analysis of Solar Organic Rankine Cycle for Geothermal Air Conditioned Net Zero Energy Buildings," 2011.

[5] S. Agrawal and G. N. Tiwari, "Exergoeconomic analysis of glazed hybrid photovoltaic thermal module air collector," *Sol. Energy*, vol. 86, no. 9, pp. 2826–2838, 2012.

[6] M. A. Rosen and I. Dincer, "Exergoeconomic analysis of power plants operating on various fuels," *Appl. Therm. Eng.*, vol. 23, no. 6, pp. 643–658, 2003.

[7] O. Ozgener and A. Hepbasli, "Exergoeconomic analysis of a solar assisted ground-source heat pump greenhouse heating system," *Appl. Therm. Eng.*, vol. 25, no. 10, pp. 1459–1471, 2005.

[8] M. A. Dincer, I., Rosen, *Exergy: energy, environment & sustainable development*. Elsevier science and technology., 2007.

[9] L. Ozgener, A. Hepbasli, I. Dincer, and M. A. Rosen, "Exergoeconomic analysis of geothermal district heating systems: A case study," *Appl. Therm. Eng.*, vol. 27, no. 8–9, pp. 1303–1310, 2007.

[10] Z. Oktay and I. Dincer, "Exergoeconomic analysis of the Gonen geothermal district heating system for buildings," *Energy Build.*, vol. 41, no. 2, pp. 154–163, 2009.

[11] E. Saloux, A. Teyssedou, and M. Sorin, "Analysis of photovoltaic (PV) and photovoltaic/thermal (PV/T) systems using the exergy method," *Energy Build.*, vol. 67, pp. 275–285, 2013.

[12] A. . Joshi, "Thermodynamic assessment of photovoltaic systems," *Sol. Energy*, vol. 83, no. 1139–1149, pp. 1–7, 2009.

[13] G. N. Tiwari, *Solar Energy: Fundamentals, Design, Modeling and Applications*. Narosa Publishing House, New Delhi and CRC Press, Washington., 2002.

[14] M. Santarelli and S. Macagno, "A thermoeconomic analysis of a PV-hydrogen system feeding the energy requests of a residential building in an isolated valley of the Alps," *Energy Convers. Manag.*, vol. 45, no. 3, pp. 427–451, 2004.

[15] J. Holmberg, C. Flynn, and L. Portinari, "The colours of the Sun," *Mon. Not. R. Astron. Soc.*, vol. 367, no. 2, pp. 449–453, 2006.

[16] A. S. Joshi, I. Dincer, and B. V. Reddy, "Thermodynamic assessment of photovoltaic systems," *Sol. Energy*, vol. 83, no. 8, pp. 1139–1149, 2009.

[17] M. A. Rosen and I. Dincer, "Exergy–cost–energy–mass analysis of thermal systems and processes," *Energy Convers. Manag.*, vol. 44, no. 10, pp. 1633–1651, 2003.

[18] H. Caliskan, I. Dincer, and A. Hepbasli, "Exergoeconomic and environmental impact analyses of a renewable energy based hydrogen production system," *Int. J. Hydrogen Energy*, vol. 38, no. 14, pp. 6104–6111, 2013.