An energy and exergy analysis of photovoltaic system in Bantul Regency, Indonesia

Arif Rahman Hakim *, Wahyu Tri Handoyo, Putri Wullandari

Loka Riset Mekanisasi Pengolahan Hasil Perikanan, Badan Riset dan Sumber Daya Manusia, Kementerian Kelautan dan Perikanan
Jl. Imogiri Barat km 11.5, Jetis, Bantul, D.I Yogyakarta 55781, Indonesia

Abstract

Energy and exergy analysis has been conducted on photovoltaic (PV) system in Bantul Regency, a special region of Yogyakarta, Indonesia. The PV exergy analysis was used to determine the performance of the PV system by considering environmental factors other than solar irradiance. This research aims to obtain values of exergy and energy efficiencies in the PV system. The experiment results show that the energy efficiency value produced by the PV system was 8.62 to 74.18%, meanwhile its exergy efficiency was 0.29% to 9.40%, respectively. The value of exergy efficiency is lower than the value of energy efficiency. This result confirmed that the environmental factor greatly affects the output of the PV system. It can be concluded that high solar radiation does not always increase the production of exergy, since it is also influenced by the environmental temperature and the PV cells' temperature.

I. Introduction

Population growth, technology advances and lifestyle increase the community needs, and one of the vital needs is energy demand. Currently, the largest source of energy comes from fossil-based (oil, gas, coal etc). However, fossil-based energy is non-renewable energy so the number will continue to decrease [1][2]. In Indonesia, The Ministry of Energy and Mineral Resources states that the reduced potential of fossil-based energy, especially for oil and natural gas, prompted the government to make Renewable Energy Sources (RES) a top priority for maintaining energy security and sustainability, given the huge potential of RES to be a mainstay in the future of national energy supply. The average growth in energy demand during the 2015-2050 period is about 4.9% per year [3].

The research about RES continues to develop along with the depletion of fossil-based energy reserves and people's concern for environmental sustainability [4][5][6]. Currently, solar energy is one of the most widely developed renewable energy sources. Tropical countries have the advantage of obtaining considerable sunshine throughout the year.

Sunlight that hits the surface of the earth can be converted into electrical energy through two ways: first, it is converted by using solar photovoltaic, and second through heating media using a solar collector that is often called solar thermal. The ability of the photovoltaic system to convert solar radiation into electrical energy is calculated based on its efficiency value (energy efficiency). The energy efficiency of PV is a ratio between the energy generated by the PV system and the total solar radiation that hits the surface of PV. Therefore, only the electrical energy generated by PV is reviewed, while other parameters such as ambient temperature, PV cell temperature, wind velocity and heat capacity are not taken into account. This is due to the calculation of energy is based on a calculation of energy based on the law of thermodynamics I, where energy in and out of the system is not influenced by the environment [7].

Some researchers have developed an analysis of the accuracy of PV performance values through the concept of exergy. This concept is based on the law of

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* Corresponding Author. Tel: +62 813 3478 1593
  E-mail address: arifrahmanh11@gmail.com

thermodynamics II, so it can provide information about the energy lost from the system associated with thermodynamic processes that occur in the system. The exergy efficiency can be used to describe the quality difference between electricity and heat. The exergy of a thermodynamic system is the maximum work that can be done by the system when it undergoes reversible processes that bring the system into complete thermodynamic equilibrium with a defined reference environment [8].

Several studies that have been conducted related to PV performance analysis, include Sahin *et al.* (2007) that has investigated the PV performance characteristics based on exergy perspective [7], and Sarhaddi *et al.* (2010) that has conducted electrical performance research, exergy components, and exergy efficiency in solar panels [9]. Saidur *et al.* (2012) has reviewed the literatures on exergy analysis of solar energy applications [10], and Pandev *et al.* (2013) has reviewed exergy analysis and parametric study of multi-crystalline solar photovoltaic systems [2].

Therefore, we need to study PV performance that is influenced by the climate of a particular region. This research is aimed to analyze the relation of environmental parameters in Bantul Regency to energy and exergy in PV system.

II. Method/Material

A. Experimental set-up and procedure

The solar photovoltaic (SPV) system that is used in this research consists of a solar panels 100 Wp with polycrystalline type and 2.4 m^2 of total area PV; solar charge controller (SCC) with MPPT (maximum power point tracking) type, and battery 100 AH type gel deep cycle DOD (depth of discharge) 30%. Figure 1 is shown the experimental view of the SPV system. The experiment is conducted during November 2017 and located in Bantul Region, Yogyakarta with coordinates Latitude -7.874818 and Longitude

110.325537. The observation time starts from 08:00 up to 16:00 (Western Indonesian Time). The observation data is solar radiation, wind velocity, ambient temperature, open-circuit voltage, short circuit current, voltage, and output current.

The instrument that is used in this research consists of Solar Power Meters (Lutron SPM-1116SD) to measure the intensity of solar energy with Watt/m² units, Anemometer (Lutron YK-2005AM) that measures wind velocity with m/s units, Thermometer (Lutron TM-946) to measure ambient temperature, and Clamp meter (Sanwa DCM2000DR) with max input DC / AC 1000V / 2000 A to measure the current, voltage, and frequency of electricity parameters.

B. Thermodynamics analysis

The obtained data from the experiment mentioned above are then analyzed using an equation which developed by Pandev *et al.* (2013) [2]. Data analysed is conducted to find out the efficiency of energy, power conversion energy and exergy. The input energy from solar radiation (Q_{in}) is given in Equation (1).

$$Q_{in} = I_s\, A \tag{1}$$

where I_s (W/m^2) is the intensity of solar radiation, and A (m^2) is an area of SPV module.

The actual output of the SPV module (Q_o) can be defined using Equation (2).

$$Q_0 = V_{oc} I_{sc} FF \tag{2}$$

where V_{oc} (V) is an open-circuit voltage, I_{sc} (A) is a short circuit current, and FF is a fill factor.

The FF of the SPV system can be defined as the ratio of the product of maximum power voltage (V_m) and the maximum power current (I_m) to the product of open-circuit voltage and short circuit current, and can be expressed from Equation (3).

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \tag{3}$$

Figure 1. Experimental view

Using the definition from Equation (3), Equation (2) can also be expressed in Equation (4).

$$Q_0 = V_m I_m \qquad (4)$$

The input exergy (Ex_{in}), *i.e.* exergy of solar radiation (Ex_{solar}) is given by Equation (5).

$$Ex_{solar} = Ex_{in} = (1 - \frac{T_a}{T_s})I_s A \qquad (5)$$

where T_s is the temperature of the sun which is taken as 5,777 K, and T_a is ambient temperature (°C).

Exergy output PV system (Ex_{out}) is given by Equation (6).

$$Ex_{out} = Ex_{elec} + Ex_{therm} \qquad (6)$$

where Ex_{elec} is electrical exergy and Ex_{therm} is thermal exergy. The calculation of electrical exergy of the PV system (Ex_{elec}) has been assumed that exergy content received by the photovoltaic surface is fully utilized to generate maximum electrical exergy ($V_{oc} I_{sc}$).

$$Ex_{elec} = E_{elec} - I' = V_{oc}I_{sc} - (V_{oc}I_{sc} - V_m I_m) \qquad (7)$$

where $V_{oc} I_{sc}$ represents the electrical energy and ($V_{oc}I_{sc}$ - $V_m I_m$) represents the electrical exergy destruction. Therefore, Equation (7) can define the electrical exergy that is shown in Equation (8).

$$Ex_{elec} = V_m I_m \qquad (8)$$

The thermal exergy of the system (Ex_{therm}) which is defined as the heat loss from the photovoltaic surface to the ambient can be represented by Equation (9).

$$Ex_{therm} = \left(1 - \frac{T_a}{T_{cell}}\right) Q \qquad (9)$$

where $Q = h_{ca} A (T_{cell} - T_a)$ and $h_{ca} = 5.7 + 3.8\,v$; where T_{cell} is cell temperature (°C), h_{ca} is the heat transfer coefficient (W/m² °C), and v is the wind velocity (m/s). Using those equations, exergy of SPV system can be written in Equation (10).

$$Ex_{pv} = V_m I_m - (1 - \frac{T_a}{T_{cell}})h_{ca} A (T_{cell} - T_a) \qquad (10)$$

The energy efficiency (η) can be defined by Equation (11).

$$\eta = \frac{V_{oc} I_{sc}}{I_s A} \qquad (11)$$

However, Equation (11) definition is restricted to theoretical cases only. The power conversion efficiency (η_{pce}) of SPV can be defined as the ratio of the actual electrical output ($V_m I_m$) to the input energy ($I_s A$) on the SPV surface and can be given in Equation (12).

$$\eta_{pce} = \frac{V_m I_m}{I_s A} \qquad (12)$$

The energy efficiency and the power conversion efficiency can be defined using Equation (11) and (12) that is shown in Equation (13).

$$\eta_{pce} = \frac{\eta V_m I_m}{V_{oc} I_{sc}} \qquad (13)$$

The power conversion efficiency can also be defined in terms of *FF* using Equation (14).

$$\eta_{pce} = FF\eta \qquad (14)$$

For variations in ambient temperature and irradiance, the cell temperature can be estimated quite accurately with the linear approximation [11] using Equation (15).

$$T_{cell} = T_a + \left[\frac{T_{NOCT}-20}{800\ W/m^2}\right]I_s \qquad (15)$$

where nominal operating cell temperature (T_{NOCT}) is defined as the cell temperature measured under open circuit when the ambient temperature is 20 °C, irradiance is 800 W/m², and wind velocity is 1 m/s. Its value is usually around 45 °C.

In general, the exergy efficiency (ψ) is defined as the ratio of output exergy to the input exergy and given by Equation (16).

$$\psi = \frac{Output\ exergy}{Input\ exergy} \qquad (16)$$

Using the Equation (16), the exergy efficiency (ψ) can be expressed in Equation (17).

$$\psi = \frac{V_m I_m - \left(1 - \frac{T_a}{T_{cell}}\right)h_{ca} A (T_{cell} - T_a)}{\left(1 - \frac{T_a}{T_s}\right)I_s A} \qquad (17)$$

III. Result and discussion

The specification of polycrystalline photovoltaic based on data from Manufacture is shown in Table 1. These data are taken from standard test condition, *i.e.* at solar radiation of 1000 W/m², air mass of 1.5 kg/m³ and ambient temperature of 25 °C.

The results of field observation data including the intensity of sunlight, wind velocity, ambient temperature (T_a), solar cell temperature (T_{cell}), current (I_{sc}) and voltage (V_{oc}) of PV, output (P) and energy efficiency (η), power conversion efficiency (η_{pce}) and exergy efficiency (ψ) are presented in Table 2. The average intensity of solar radiation during November 2017 from 08:00 up to 16:00 is 76.47 to 604.43 Watt/m². In the morning, the intensity of solar radiation is low, then it increases during the day and backs down in the afternoon. The intensity of solar radiation in November tends to be low as it is the rainy season.

Furthermore, the value of wind velocity has the same pattern, nearly equal to the intensity of solar radiation; where the value of wind velocity is low in the morning and in the afternoon but high during the

Table 1.
Specification of polycrystalline PV

Paramaters	Value
Output Power (P_{max})	100 wp
Max Power Voltage (V_{pm})	18.0 Volt
Max Power Current (I_{pm})	5.60 Ampere
Open Circuit Voltage (V_{oc})	22.6 Volt
Short Circuit Current (I_{sc})	6.02 Ampere
Module Efficiency	15%
Operating Module Temperature	-40 °C to +85 °C
Maximum System Voltage	1000 V DC
Maximum Series Fuse Rating	20 A
Power Tolerance	± 3%

Table 2.
Result of field observation and analyze

Time	Solar Radiation (Watt/m²)	Wind Velocity (m/sec)	T_a (°C)	T_{cell} (°C)	I_{sc} (A)	V_{oc} (V)	V_m (V)	I_m (A)	FF	P (W)	η (%)	η_{pce} (%)	ψ (%)
08:00	247.08	0.01	30.23	36.41	6.77	19.42	14.50	3.85	0.42	55.83	22.17	9.41	7.02
08:30	373.47	0.09	31.32	40.65	6.78	19.05	16.00	4.58	0.57	73.33	14.42	8.18	4.74
09:00	415.95	0.09	31.92	42.32	6.79	18.85	16.33	4.63	0.59	79.49	12.82	7.58	3.89
09:30	421.07	0.14	32.15	42.68	6.79	18.77	15.83	5.12	0.64	81.01	12.62	8.02	4.20
10:00	434.43	0.26	32.32	43.18	6.80	18.71	16.00	5.07	0.64	81.07	12.20	7.78	3.58
10:30	327.82	0.22	32.53	40.73	6.80	18.64	15.33	4.43	0.54	67.98	16.10	8.64	5.38
11:00	307.10	0.40	31.55	39.23	6.79	18.97	14.83	5.53	0.64	82.08	17.47	11.14	7.65
11:30	604.43	0.35	33.35	48.46	6.81	18.36	16.50	5.07	0.67	83.60	8.62	5.76	0.29
12:00	333.22	0.35	32.23	40.56	6.79	18.74	15.33	4.45	0.54	68.23	15.92	8.53	4.96
12:30	272.55	0.42	30.27	37.08	6.77	19.41	15.83	4.63	0.56	73.36	20.08	11.22	7.91
13:00	241.63	0.49	30.95	36.99	6.78	19.18	16.33	3.92	0.49	63.97	22.41	11.03	7.99
13:30	362.63	0.51	30.90	39.97	6.78	19.19	16.33	3.60	0.45	58.80	14.95	6.76	2.43
14:00	307.47	0.36	30.87	38.55	6.78	19.21	16.33	2.88	0.36	47.09	17.64	6.38	2.87
14:30	178.95	0.14	29.88	34.36	6.76	19.54	15.17	3.15	0.36	47.78	30.77	11.12	9.15
15:00	106.20	0.36	28.78	31.44	6.75	19.91	14.83	1.85	0.20	27.44	52.73	10.77	9.32
15:30	86.28	0.23	28.05	30.21	6.74	20.16	14.17	1.53	0.16	21.72	65.62	10.49	9.36
16:00	76.47	0.26	27.93	29.85	6.74	20.20	14.17	1.35	0.14	19.13	74.18	10.42	9.40

day. The value of wind velocity during the day is ranged from 0.01 to 0.51 m/s. The average of environmental temperature reaches the lowest value at 16:00 with the value of 27.93 °C, and reaches the highest value at 11:30 with the value of 33.35 °C. The increasing of solar radiation intensity will cause the environmental temperature to rise. The relation between the intensity of solar radiation with environmental temperature is presented in Figure 2.

Furthermore, an increase in ambient temperature (T_a) will trigger an increase in cell temperature (T_{cell}). In addition, cell temperature (T_{cell}) is also affected by the nominal operating temperature (T_{NOCT}). If the fill factor (FF) value of a solar cell is higher, the solar cell output (P) and power conversion efficiency (η_{pce}) will be better. The value of FF depends greatly on the value of multiplication of V_{oc} and I_{sc} (see Equation (3)). However, the price of V_{oc} and I_{sc} is closely related to
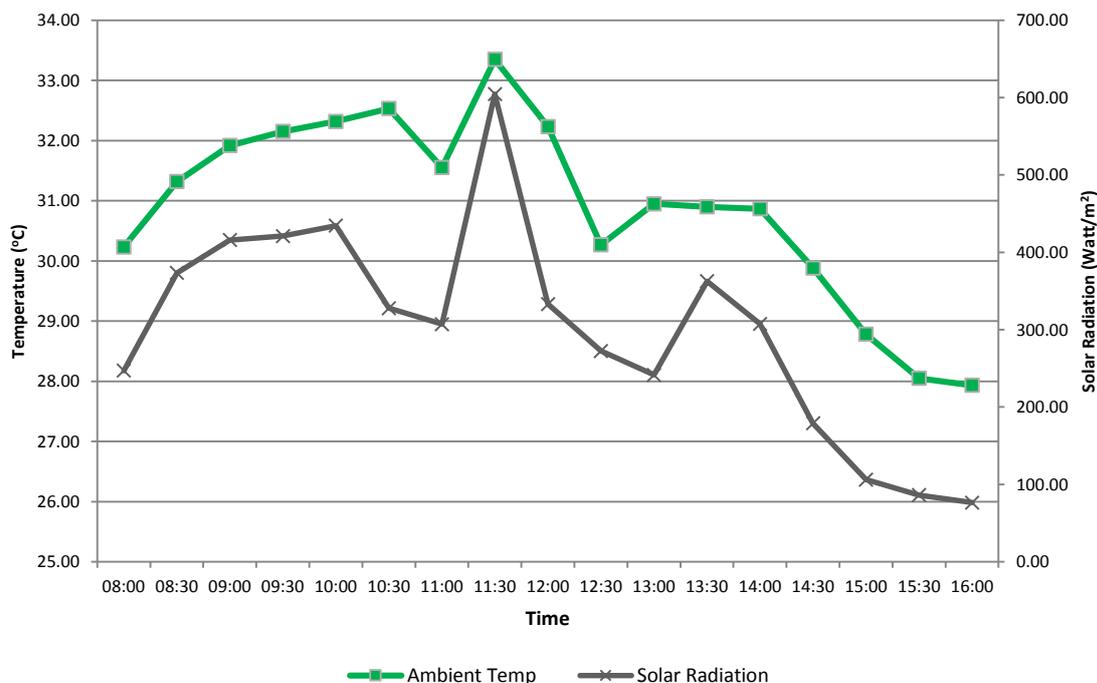

Figure 2. The relationship intensity of solar radiation with ambient temperature

the material of the semi conductor. The V_{oc} and I_{sc} value are reversed for a given type of semiconductor material. The semiconductor material that has a large Eg (Energy gap) will have a large V_{oc} value and a small I_{sc} value, vice versa. The value of FF in this study is 0.14 to 0.67. The highest FF value is reached at a maximum solar intensity (Figure 3).

Exergy is the maximum amount of net work obtained when the material flow is brought from the initial state to the dead state through a process involving interaction with the environment only. A system is considered to be in a dead state when it is in thermal, mechanical, and chemical equilibrium with the environment. In the analysis, it is important to understand the difference between energy and exergy. It is also important to consider the quality and quantity of energy used to achieve a particular goal and in reality to achieve the efficient and effective use of energy resources. One of the main uses of the exergy concept is the balance of exergy in the thermal systems analysis. Exergy balance (exergy analysis) can be viewed as a declaration of energy degradation law. Exergy analysis is a method for identification of the type, location and amount of thermal loss. The identification and qualification of these losses allow us to evaluate and improve thermal system design [12].

Electrical exergy (Ex_{elec}) produced by PV in this study is ranged from 19.13 to 83.60 W. The largest electrical exergy (Ex_{elec}) is at 11:30 and the lowest is at 16:00. Electrical exergy (Ex_{elec}) values have the same pattern of solar radiation (I_s) received in PV. If the solar radiation (I_s) received by the PV surface is higher, it will result in greater electrical exergy (Ex_{elec}). Based on Equation (8), the high value of solar radiation (I_s) will produce a large current (I_m) and voltage (V_m). However, when compared to the

produced PV exergy (Ex_{pv}), the value of electrical exergy (Ex_{elect}) does not reflect the same pattern (Figure 4).

In the highest electrical exergy (Ex_{elec}) conditions, the value of exergy PV (Ex_{pv}) is precisely the lowest. Exergy PV (Ex_{pv}) value is between 4.22 to 56.07 W. The lowest exergy value occurs at 11:30 when the solar radiation (I_s) obtain the highest value. Increasing ambient temperatures (T_a) results in increasing thermal exergy (Ex_{therm}) and decreasing exergy PV (Ex_{pv}) in the system (Figure 5). Energy efficiency (η) is obtained from V_{oc} and I_{sc} values as electrical output compared to solar radiation per unit area on the PV surface as the energy input. Energy efficiency (η) is only theoretical value since it has not calculated the value of fill factor (FF). The energy efficiency (η) being produced by PV during the experiment is 8.62% to 74.18%. The lowest value at the middle day (11.30) is 8.62%, while the highest value at 16:00 is 74.18% (Figure 5). The actual picture of the energy conversion production is obtained from the value of power conversion energy (PCE). PCE values vary between 5.76% to 11.22% (Figure 6), lower than the value of energy efficiency (η).

Factor that affects the value of energy conversion is fill factor (FF), which is the value of the maximum power output ratio of PV with the theoretical power (I_{sc}, V_{oc}) PV output. When the value of energy efficiency is high and the FF is small, then the energy conversion value will be small. The maximum output of PV is the result of the current value (I_m) and voltage (V_m) of PV that is influenced by the intensity of solar radiation (Watt/m²).

Exergy efficiency value of PV (Equation (17)) can be obtained from electrical exergy output minus thermal exergy then compared with exergy input.
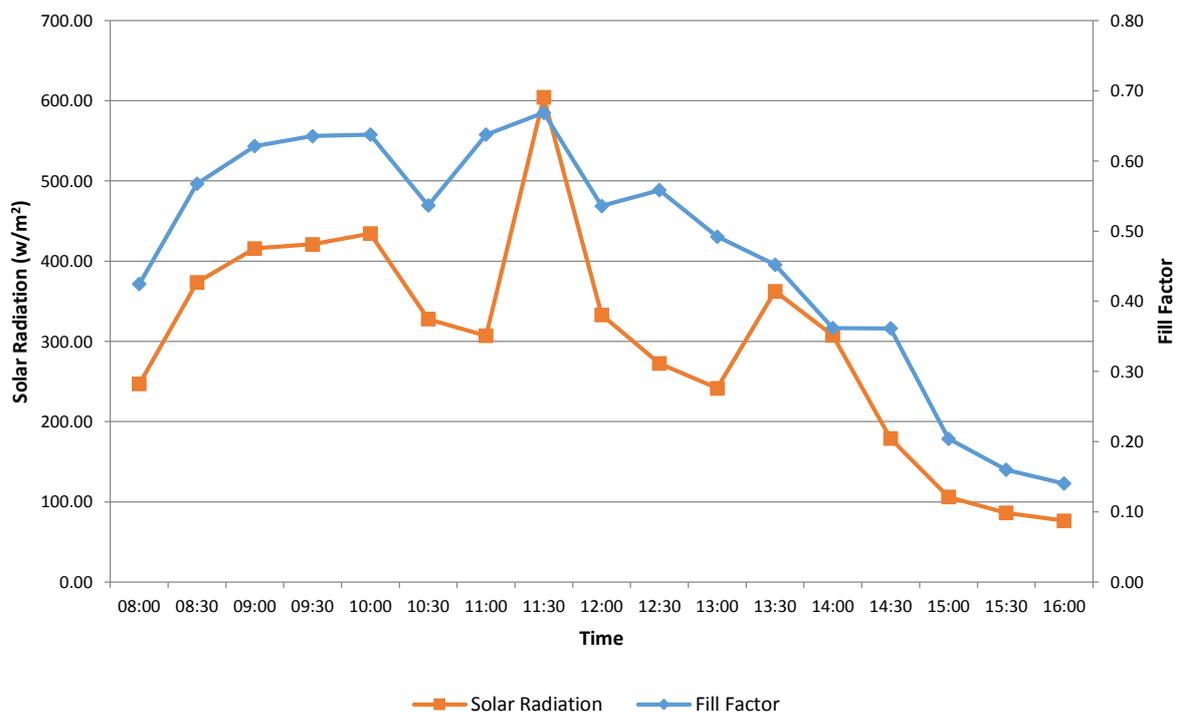

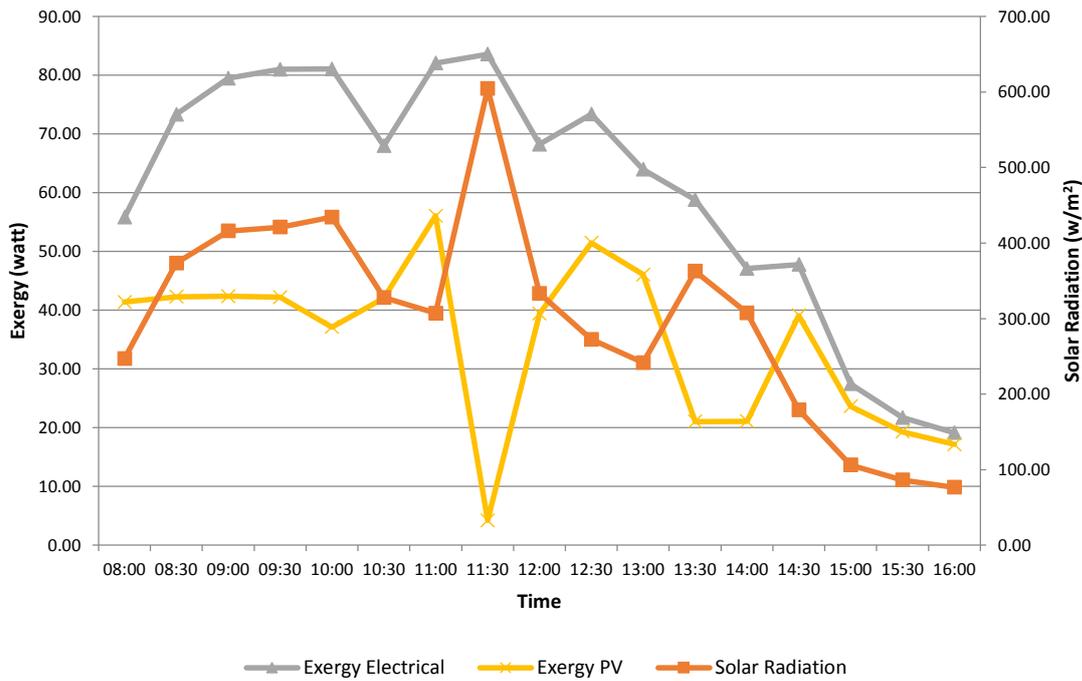Figure 3. Effect of solar radiation on fill factor

Figure 4. The relationship between solar radiation, electrical exergy, and exergy photovoltaic
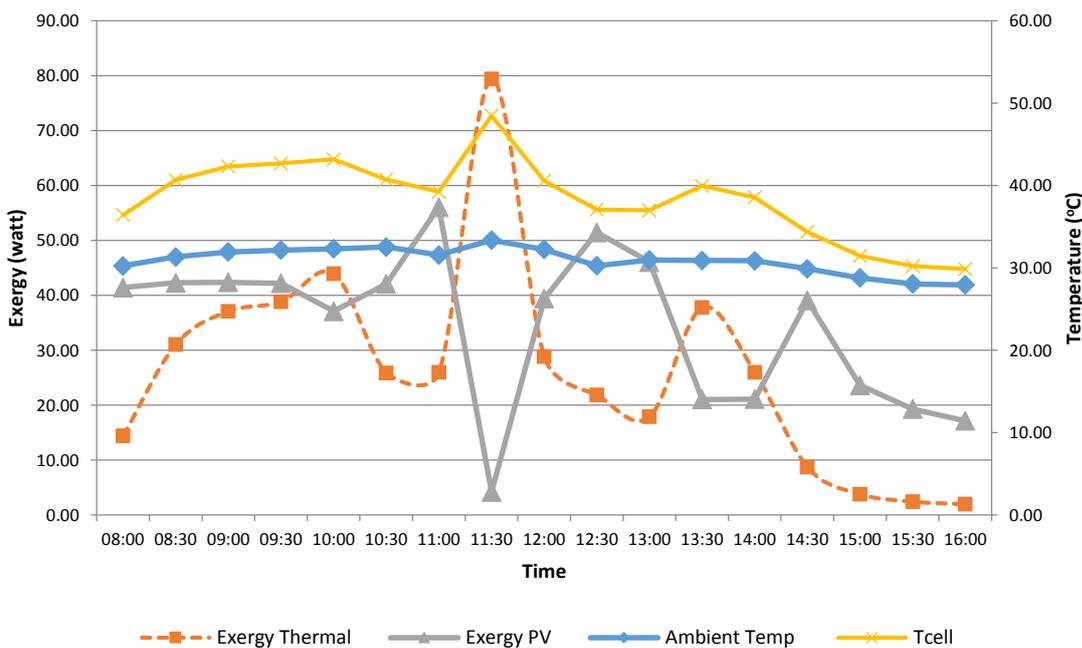

Figure 5. The relationship between ambient temperature and exergy thermal

Exergy value is ranged from 0.29% to 0.40%, with the lowest value at 11:30, 603.43 Watt/m² solar radiation intensity, and 33.35 °C environmental temperature. The increasing of environmental temperature also increase the solar cell temperature to become 48.46 °C, while the highest efficiency value is 9.40% at 16:00. During that time, the intensity of solar radiation reaches the lowest value as well as the environmental temperature.

IV. Conclusion

The value of energy efficiency (η) produced by PV is 8.62% to 74.18% while its exergy efficiency (ψ) is 0.29% to 9.40%, respectively. The value of the exergy efficiency (ψ) is much lower than the energy efficiency (η) being produced. Environmental factors greatly affect the output of PV. Large solar radiation does not directly increase the exergy output. The exergy output is strongly influenced by the
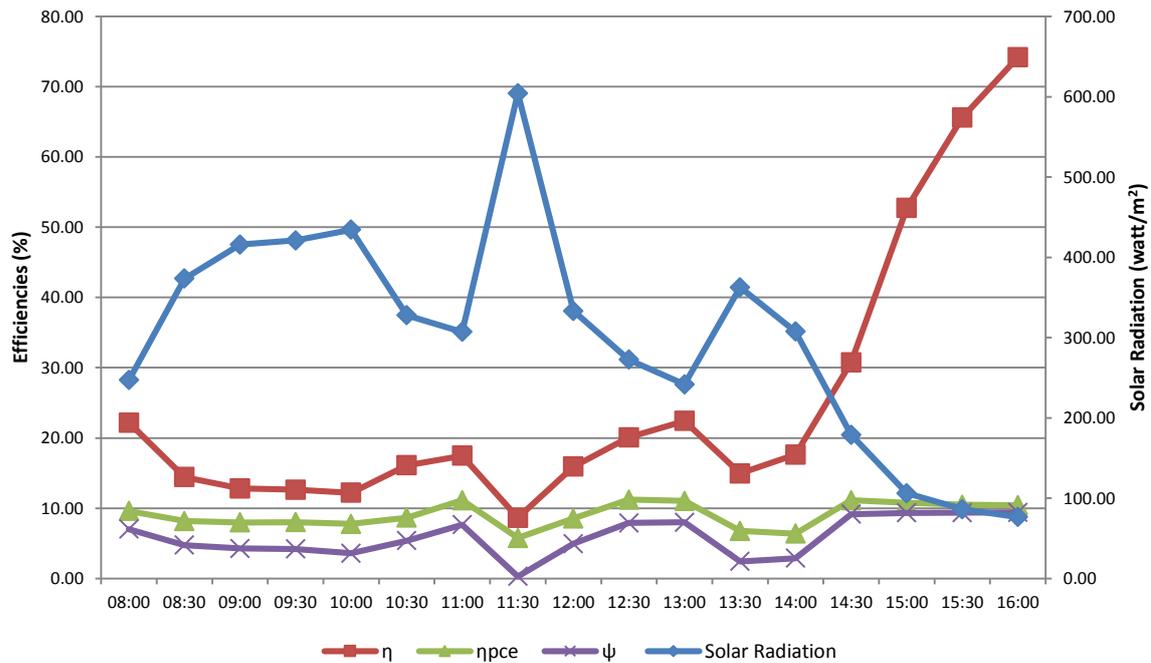
Figure 6. Variation of different efficiencies and solar radiation

environmental temperature and temperature of PV cells. The high environmental temperature in Bantul Regency and low solar intensity at the time of the research have affected the performance of the photovoltaic system.

Acknowledgement

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