

CORRELATION ANALYSIS OF LIGHT INTENSITY ON THE EFFICIENCY AND PHOTOCURRENT RESPONSIVITY OF SOLAR PANELS IN BENGKULU CITY

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Abstract

The efficiency of solar panels is generally influenced by the installation tilt angle, as it affects the amount of sunlight absorbed and the detector's response in converting light intensity into electrical energy. This study aims to analyze the relationship between light intensity, efficiency, and photocurrent responsivity of monocrystalline solar panels based on experimental data collected in Bengkulu City. The research method employed correlation and linear regression analysis to evaluate the relationships between light intensity, efficiency, and photocurrent responsivity at tilt angles of 0°, 30°, and 60° Degree. The results indicate that the highest efficiency of 15% was achieved at a 0° tilt, even though the highest light intensity of 146,467 lux occurred at a 60° tilt. The relationship between light intensity and efficiency is nonlinear, although a positive correlation was observed, with the highest regression coefficient of 0.0000006x and the highest coefficient of determination (R^2) of 39.19% found at a 30° tilt. Conversely, the relationship between light intensity and photocurrent responsivity exhibited a negative correlation, with the highest regression coefficient of -0.0000001x and the highest R^2 of 25.98% at a 60° tilt. These findings suggest that the linear relationship between light intensity and both efficiency and photocurrent responsivity is relatively weak, likely due to other dominant factors affecting the performance of the solar panel.

Keywords: solar cell, efficiency, photocurrent responsivity, correlation, linear regression

Abstrak

Efisiensi panel surya umumnya dipengaruhi oleh sudut kemiringan pemasangan, karena sudut tersebut menentukan tingkat penyerapan cahaya matahari oleh panel dan respons detektor dalam mengonversi intensitas cahaya menjadi energi listrik. Penelitian ini bertujuan untuk menganalisis hubungan antara intensitas cahaya terhadap efisiensi dan photocurrent responsivity pada panel surya monokristalin berdasarkan data eksperimen di Kota Bengkulu. Metode yang digunakan adalah analisis korelasi dan regresi linear terhadap data intensitas cahaya, efisiensi, dan photocurrent responsivity pada tiga sudut kemiringan, yaitu 0°, 30°, dan 60°. Hasil menunjukkan bahwa efisiensi tertinggi sebesar 15% diperoleh pada sudut kemiringan 0°, meskipun intensitas cahaya tertinggi sebesar 146.467 lux tercatat pada sudut 60°. Hubungan antara intensitas cahaya dan efisiensi bersifat nonlinier, namun secara statistik menunjukkan korelasi positif, dengan nilai koefisien regresi tertinggi sebesar 0,0000006x pada sudut 30°, dan koefisien determinasi (R^2) tertinggi sebesar 39,19%. Sebaliknya, hubungan antara intensitas cahaya dan photocurrent responsivity menunjukkan korelasi negatif, dengan koefisien regresi tertinggi sebesar -0,0000001x pada sudut 60°, dan R^2 tertinggi sebesar 25,98%. Hasil ini mengindikasikan bahwa hubungan antara intensitas cahaya terhadap efisiensi dan photocurrent responsivity tidak sepenuhnya kuat secara linear, yang kemungkinan disebabkan oleh faktor-faktor lain yang lebih dominan memengaruhi performa panel surya.

Kata Kunci: Sel surya, efisiensi, photocurrent responsivity, korelasi, linear regresi.

INTRODUCTION

The utilization of solar panels as a renewable energy source is thriving to promote a clean energy transition. Various photovoltaic (PV) panels are circulating among the public, including monocrystalline, polycrystalline, and thin-film technologies. The efficiency of solar panels is not only influenced by the type of solar cell but also by environmental factors such as light intensity and the panel's tilt angle (Ridho et al., 2023); (Abdurahman et al., 2023); (Sartono et al., 2021); (Marpaung & Purba, 2024). The incident light and the panel tilt angle significantly influence the optimal efficiency of solar panels. This parameter refers to the ratio between the short-circuit current (I_{sc}) and the incident light intensity or solar irradiance. Responsivity is influenced by irradiation levels, depending on the light detector employed. Non-linear photo response under low irradiance conditions has been widely reported in thin-film solar panels (Pekkola et al., 2018). Examining both efficiency and photocurrent responsivity offers valuable insights into optimizing the performance of solar panels across various regions, including tropical climates such as Indonesia.

Bengkulu City has a tropical climate characterized by varying light intensity throughout the day. As a result, solar panels do not consistently operate under the ideal conditions specified by manufacturers. Weather fluctuations significantly contribute to the discrepancy between the actual output and the expected power, as solar panel performance is typically defined under Standard Test Conditions (STC). The gap between STC and actual operating conditions is a common challenge. Solar input and output power decline with decreasing solar irradiance, particularly in the late afternoon (Abdurahman et al., 2023).

Previous studies have examined the effect of tilt angle on the electrical characteristics of solar panels. According to Marpaung & Purba (2024), solar panels on tilt angles of 15°, 30°, and 45° revealed the highest efficiency of 13.7% at a 30° tilt. Measurements conducted from 10:00 to 15:00 indicated that solar irradiance peaked around noon (12:00-13:00). In contrast, Mardani et al. (2022) reported that the optimal efficiency of 15.47% occurred at a tilt angle of 10° at 15:00 WIB, while the lowest efficiency of 6.59% around midday (noon) at a tilt of 60°. Another study by Anoi et al. (2019) found that the highest efficiency, 46.83%, occurred at a tilt of 16° at 16:00. Abdurahman et al. (2023) also found that the highest efficiency of 16.82% occurred at a 15° tilt at 09:00 WIB, while at 60°, the panel reached an efficiency of 16.2% at 17:00 WIB. These findings suggest that the optimal tilt angle for maximum efficiency varies across studies. This variation is likely due to the geographic location of the study area, where the solar incidence angle differs by latitude. Additionally, seasonal and weather conditions during data collection can affect the results. Interestingly, several studies indicate that peak efficiency tends to occur in the late afternoon, which contradicts the typical assumption that output power correlates positively with solar irradiance. This increased efficiency at lower irradiance levels may be influenced by other factors, such as panel temperature and ambient humidity (Sarmah et al., 2023).

Previous studies have shown that the efficiency of solar panels based on tilt angle depends on regional conditions and weather. Furthermore, the observed decline in solar panel efficiency during the late afternoon is likely related to the panel's photocurrent responsivity. Therefore, this study aims to contribute to the existing body of knowledge by investigating the relationship between light intensity, efficiency, and photocurrent responsivity of solar panels. This research is crucial for optimizing solar panel system designs, especially in tropical regions. The objective of this study is to

analyze the relationship between light intensity, efficiency, and photocurrent responsivity of monocrystalline solar panels based on experimental data collected in Bengkulu City. The scope of this research is limited to field measurements conducted under natural sunlight across varying temporal and weather conditions.

METHODS

The method used in this study is correlation analysis aimed at predicting the efficiency and photocurrent responsivity of solar panels in response to light intensity. The research location is in Sukarami area, Selebar District, Bengkulu City. The location coordinates are 30°49'48" S and 102°20'32" E. Data collection was conducted in June 2024.

Data were collected through direct measurements using the AS803 lux meter to measure light intensity. The solar panel used was a 50 Wp monocrystalline type. The detailed specifications of the solar panel are shown in Table 1. A digital multimeter has measured the voltage and current of the solar panel. Data collection in this study was conducted through direct measurements every 2 hours from 06:00 to 18:00 WIB. Panel tilt angle variations of 0°, 30°, and 60° facing the direction of sunlight were also applied. The parameters observed in this test were open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), and light intensity (lux).

Tabel 1. Monocrystalline Solar Panel Specifications

parameter	Value
<i>Rated Maximum Power (P_m)</i>	50 W
<i>Tolerance</i>	3%
<i>Voltage at P_{max} (V_{mp})</i>	18,4 V
<i>Current at P_{max} (I_{mp})</i>	2,72 A
<i>Open-Circuit Voltage (V_{oc})</i>	22,6 V
<i>Short-Circuit Current (I_{sc})</i>	2,94 A
<i>Normal Operating cell Temp (NOCT)</i>	46±2° C

The efficiency of the solar panel is obtained by determining its input and output power. The input power of the solar panel is determined using Equation (1). P_{in} represents the input power from solar radiation (Watts), E is the solar radiation intensity (Watts/m²), and A is the surface area of the solar panel (m²).

$$P_{in} = E \times A \tag{1}$$

Meanwhile, the output power can be determined using Equation (2). The output power depends not only on the open-circuit voltage and short-circuit current, but also on the fill factor of the panel. The fill factor refers to how much maximum power the solar panel can produce compared to its ideal power. V_{oc} is the open-circuit voltage of the solar panel (volts), I_{sc} is the short-circuit current of the panel (amperes), FF is the fill factor, and P_{out} is the output power of the panel (watts).

$$P_{out} = V_{oc} \times I_{sc} \times FF \tag{2}$$

The efficiency value is shown in Equation (3), which is the percentage ratio of output power to input power.

$$\eta = \frac{P_{out}}{P_{opt}} \quad (3)$$

In addition, the photocurrent responsivity (PR) was obtained from Equation (4), which is the ratio of the panel's short-circuit current (I_{sc}) to the optical power received by the detector (P_{opt}). The value of photocurrent responsivity is directly related to the response of the light detector in converting light intensity into electric current.

$$PR = \frac{I_{sc}}{P_{opt}} \quad (4)$$

RESULTS AND DISCUSSION

This study aims to analyze the relationship between light intensity and solar panel efficiency under different tilt angles. The experiment also investigates the photocurrent responsivity of the panel under each tilt condition. The correlation between light intensity and efficiency variation at each tilt angle will be examined using the linear regression method. The same approach also applied to the relationship between light intensity and photocurrent responsivity. Table 2 presents the measurement results of solar panel efficiency and photocurrent responsivity under a tilt angle of 0°.

Table 2. The measurement results of solar panel efficiency and photocurrent responsivity in relation to light intensity from 06:00 to 18:00 WIB at a 0° tilt angle on days 1 and 2

Time	Day 1					Day 2				
	Light Intensity (lux)	V_{oc} (volt)	I_{sc} (A)	η	PR	Light Intensity (lux)	V_{oc} (volt)	I_{sc} (A)	η	PR
06.00	452	7,26	0,35	3%	0,220	746	8,29	0,31	3%	0,184
08.00	2.830	12,98	0,38	7%	0,104	46.843	12,29	0,32	6%	0,111
10.00	7.940	19	0,39	12%	0,066	104.033	19,17	0,33	10%	0,065
12.00	131.833	18,88	0,4	12%	0,066	40.820	24,84	0,36	15%	0,048
14.00	33.460	19,58	0,4	13%	0,063	48.133	19,12	0,37	11%	0,065
16.00	84.763	19,45	0,38	12%	0,064	13.820	19	0,39	12%	0,066
18.00	1.284	16,12	0,36	9%	0,080	1.039	16,93	0,38	10%	0,075

Based on the data obtained in the study for a tilt angle of 0°, the highest efficiencies on day 1 and day 2 were recorded at a light intensity of 33,460 lux at 2:00 PM with 13% efficiency and 40,820 lux at noon with 15% efficiency, respectively. High light intensity does not necessarily result in high efficiency, as observed at noon on day 1 when the light intensity reached 131,833 lux but yielded only 12% efficiency. On day 2, the highest light intensity occurred at 10:00 AM with 104,033 lux, yet the efficiency recorded was only 10%. This phenomenon may occur due to the influence of solar panel module temperature under high light intensity conditions. High light intensity indicates high solar radiation, which increases the temperature of the solar panel and reduces its efficiency in converting light into electrical energy. According to Sarmah et al. (2023), solar cell efficiency decreases as temperature increases. This decrease in

efficiency also indicates that rising temperature leads to a reduction in voltage, which consequently reduces the output power. The results of the current study also show that afternoon conditions do not significantly affect efficiency improvement. On both day 1 and day 2, the afternoon efficiency ranged between 9% and 12%.

The correlation between light intensity and efficiency at a panel tilt angle of 0° is presented in Figure 1. The obtained linear regression relationship indicates that efficiency changes slightly with increasing light intensity. However, the correlation suggests that light intensity has a positive impact, as indicated by the linear regression equation $0.00000003x + 0.0844$, which contains a positive coefficient (0.00000003). According to this equation, the solar panel efficiency increases by 0.00000003% for every unit increase in light intensity. However, the coefficient of determination (R^2) indicates that only 16.33% of the variation in efficiency can be explained by this linear regression model. Thus, the linear relationship between light intensity and efficiency is not particularly strong under the 0° tilt condition. Other factors are likely to have a more dominant influence than light intensity.

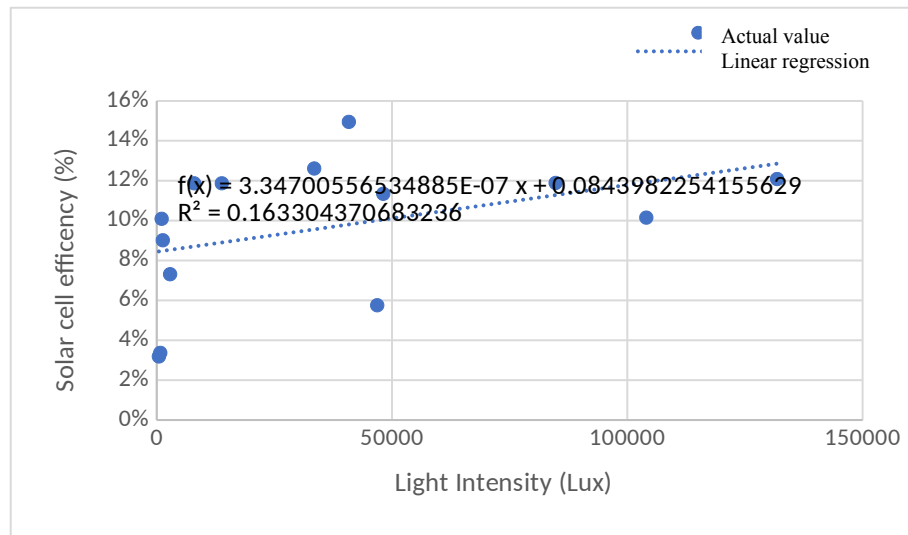


Figure 1. Variation of efficiency at a 0° tilt angle with respect to light intensity

Based on the obtained photocurrent responsivity data, the highest values were recorded as 0.22 A/W and 0.18 A/W at 6:00 AM on both measurement days at a tilt angle of 0°. The lowest values were 0.063 A/W at 2:00 PM on day 1 and 0.048 A/W at noon on day 2. The lowest responsivity occurred at the times of highest efficiency on both days. According to Zyoud (2024), extremely high light intensity can cause saturation and limit the increase in photocurrent, even though energy conversion efficiency may improve.

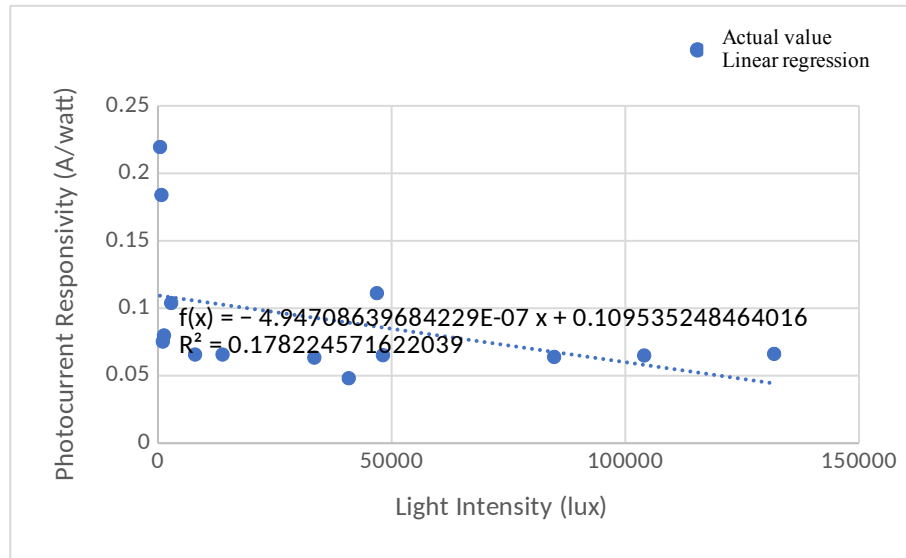


Figure 2. Variation of photocurrent responsivity at a 0° tilt angle with respect to light intensity

The statement by Rauer et al. (2024) reinforces the previously discussed findings, indicating that an increase in efficiency may also influence the short-circuit current parameter, which is associated with photocurrent responsivity. Figure 1 shows that the photocurrent responsivity has a negative coefficient of $-0.00000005x$, indicating a decline in responsivity as light intensity increases. However, the R^2 coefficient indicates that only 17.82% of the variation in photocurrent responsivity can be explained using the linear regression model. Therefore, the linear relationship between light intensity and photocurrent responsivity is not particularly strong under the 0° tilt condition.

Table 3 presents the efficiency and photocurrent responsivity data measured under a panel tilt angle of 30°. According to the measurements, the highest efficiency on the first day at a 30° tilt angle was 12%, observed between 12:00 and 14:00 WIB. The weather conditions on the first day were cloudy with rain. On the second day, the highest efficiency was 13%, recorded between 12:00 and 16:00 WIB. The weather on the second day included rain in the morning and late afternoon. Under the 30° tilt angle, weather conditions had a notably dominant influence on the measurements. That is indicated by the fluctuations in light intensity on both the first and second days. Solar light intensity fluctuates due to cloud cover or obstruction by other objects, such as shadows (Hamdani et al., 2021). The highest light intensity on day one was 56,813 lux at 10:00 WIB with an efficiency of 11%, while on day 2 it reached 137,367 lux at 14:00 WIB with an efficiency of 13%. Compared to the 0° tilt angle, the light intensity recorded on the second day under the 30° tilt condition was relatively stable between 12:00 and 14:00 WIB, with values exceeding 100,000 lux.

Table 3. Measured solar panel efficiency and photocurrent responsivity in response to light intensity from 06:00 to 18:00 WIB at a 30° tilt angle on Day 1 and Day 2

Time	Day 1					Day 2				
	Light Intensity (lux)	V_{oc} (volt)	I_{sc} (A)	η	PR	Light Intensity (lux)	V_{oc} (volt)	I_{sc} (A)	η	PR
06.00	160	9,04	0,29	4%	0,164	20	4,86	0,31	2%	0,384
08.00	10.827	11,82	0,37	6%	0,116	11.690	18,26	0,39	11%	0,069
10.00	56.813	18,89	0,38	11%	0,066	51.660	19,61	0,37	12%	0,063
12.00	31.707	18,91	0,41	12%	0,066	117.800	19,35	0,41	13%	0,064

Time	Day 1					Day 2				
	Light Intensity (lux)	V_{oc} (volt)	I_{sc} (A)	η	PR	Light Intensity (lux)	V_{oc} (volt)	I_{sc} (A)	η	PR
06.00	160	9,04	0,29	4%	0,164	20	4,86	0,31	2%	0,384
08.00	10.827	11,82	0,37	6%	0,116	11.690	18,26	0,39	11%	0,069
10.00	56.813	18,89	0,38	11%	0,066	51.660	19,61	0,37	12%	0,063
14.00	25.283	17,88	0,41	12%	0,070	137.367	19,5	0,4	13%	0,064
16.00	22.467	17,79	0,38	11%	0,071	53.607	19,7	0,41	13%	0,063
18.00	1.501	16,76	0,35	9%	0,076	123	2,79	0,37	1%	0,885

The correlation between light intensity and efficiency at a panel tilt angle of 30° shown in Figure 3. The linear regression analysis indicates that the efficiency exhibits insignificant change, similar to that observed at a 0° tilt angle. However, based on the correlation, light intensity has a positive effect, as reflected by the linear regression equation shown $0.00000006x + 0.06910$, which has a positive coefficient (0.00000006). This equation suggests that the solar panel efficiency increases by 0.00000006% for every unit increase in light intensity. Nevertheless, the coefficient of determination (R^2) shows that only 39.19% of the variation in efficiency can be explained by this linear regression model. Therefore, the linear relationship between light intensity and efficiency is stronger for the panel tilted at 30° compared to that at 0°.

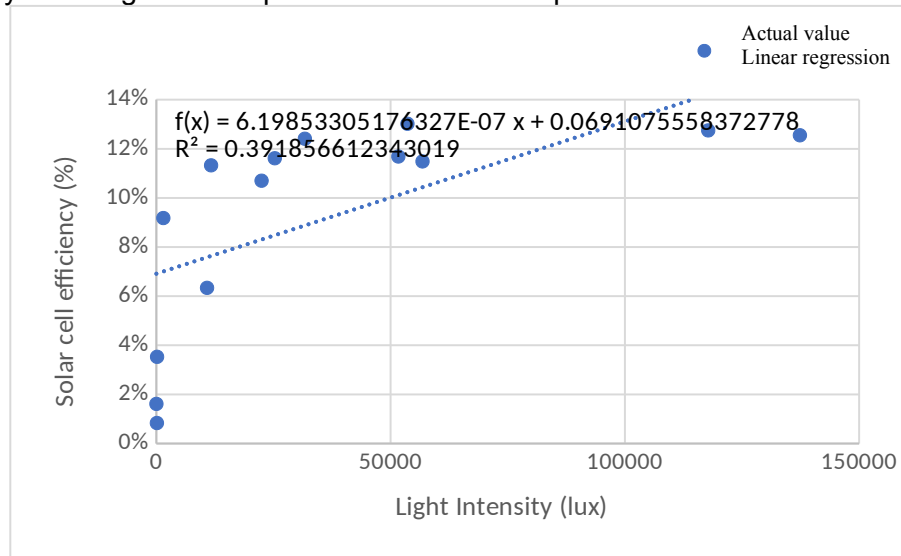


Figure 3. Variation of efficiency at a 30° tilt angle with respect to light intensity

Based on the photocurrent responsivity data obtained from measurements of the solar panel tilted at 30°, the highest value recorded on the first day was 0.164 A/Watt at 06:00 WIB, whereas on the second day, the highest value reached 0.885 A/Watt at 18:00 WIB. Figure 4 illustrates the correlation between light intensity and photocurrent responsivity.

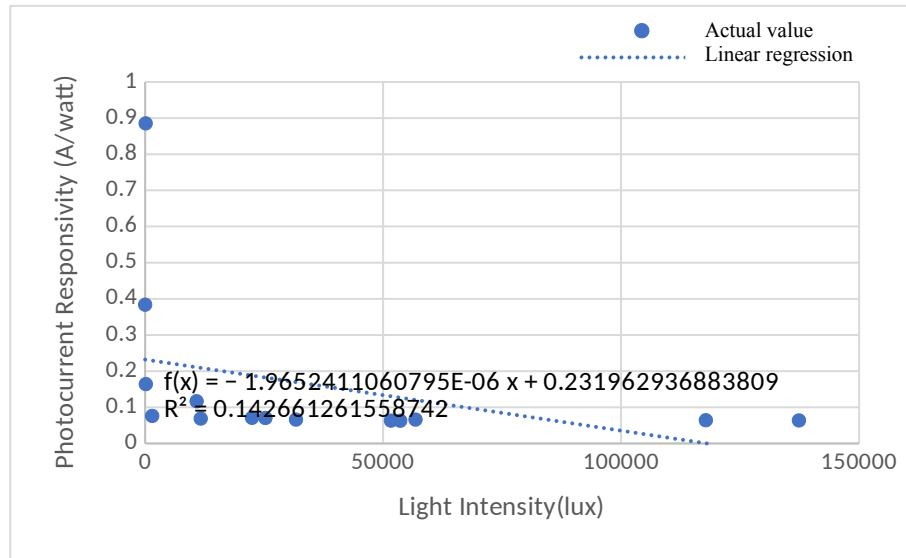


Figure 4. Variation of photocurrent responsivity at a 30° tilt angle with respect to light intensity

The linear regression results indicate that the photocurrent responsivity has a negative regression coefficient of -0.0000002 , implying that as light intensity increases, the photocurrent responsivity decreases by 0.0000002 A/Watt. Furthermore, the coefficient of determination shows a value of 14.27%, which is lower than that of the panel tilted at 0° . Therefore, the linear relationship between light intensity and photocurrent responsivity at a 30° tilt angle is relatively weak.

At a panel tilt angle of 60° , the solar panel efficiency shown in Table 4. Based on the data, the highest efficiency during the first measurement was 12% at 14:00 WIB with a light intensity of 106,233 lux. In the second measurement, the highest efficiency increased to 13% at 16:00 WIB, despite the lower light intensity of 14,183 lux. On the first day, the highest light intensity was 137,566 lux at 12:00 WIB, corresponding to an efficiency of 10%. On the second day, the light intensity peaked at 146,467 lux, with an efficiency of 12%. Concerning photocurrent responsivity, the highest value on the first day was 0.576 A/Watt at 16:00 WIB. On the second day, the highest photocurrent responsivity was 0.280 A/Watt at 06:00 WIB. Based on the data from tilt angles of 0° , 30° , and 60° , there was no significant difference in efficiency and photocurrent responsivity. However, the data indicate that the highest photocurrent responsivity occurs under extreme conditions, namely at low light intensities. This result is consistent with Hertkorn et al. (2017), who stated that photocurrent density often exhibits a non-linear dependence on light intensity, especially at low illumination levels. Moreover, the Fill Factor affects the short-circuit photocurrent such that a reduction in the Fill Factor leads to a rise in the short-circuit photocurrent (Liu et al., 2017).

Table 4. Measurement results of efficiency and photocurrent responsivity of solar panels against light intensity from 06:00 to 18:00 WIB at a 60° tilt angle on days 1 and 2

Time	Light Intensity (lux)	Day 1				Day 2				
		V_{oc} (volt)	I_{sc} (A)	η	PR	Light Intensity (lux)	V_{oc} (volt)	I_{sc} (A)	η	PR
06.00	21	5,79	0,3	2%	0,299	75	6,08	0,28	2%	0,280
08.00	12.717	18,51	0,31	9%	0,068	22.513	17,72	0,38	11%	0,071
10.00	82.423	17,89	0,33	9%	0,070	74.933	19,49	0,38	12%	0,064

Time	Day 1					Day 2				
	Light Intensity (lux)	V_{oc} (volt)	I_{sc} (A)	η	PR	Light Intensity (lux)	V_{oc} (volt)	I_{sc} (A)	η	PR
12.0 0	137.566	19,2	0,32	10%	0,065	146.467	19,88	0,38	12%	0,062
14.0 0	106.233	19,88	0,38	12%	0,062	13.987	18,03	0,41	12%	0,070
16.0 0	261	3,69	0,37	1%	0,576	14.183	18,93	0,42	13%	0,066
18.0 0	1.049	9,67	0,39	5%	0,150	402	6,75	0,36	3%	0,242

The correlation between light intensity and efficiency at a panel tilt angle of 60° shown in Figure 5. Based on the linear regression analysis, the changes in efficiency are not significantly different compared to tilt angles of 0° and 30°. However, the correlation analysis indicates that light intensity has a positive impact on efficiency, as described by the linear regression equation is $0.00000005x + 0.0597$, with a positive coefficient (0.00000005). This suggests that the solar panel's efficiency increases by 0.00000005% for every one-unit increase in light intensity. Nevertheless, the coefficient of determination ($R^2 = 35.8\%$) indicates that only a portion of the variation in efficiency can be explained by this linear regression model. Among the three tilt angles (0°, 30°, and 60°), the 30° tilt angle exhibits the best correlation, as evidenced by the highest slope and R^2 value. Meanwhile, the decreasing R^2 trend at 60° implies the possible existence of an optimal tilt angle where the relationship between light intensity and efficiency is more linear, indicating greater system sensitivity and performance under optimal orientation.

The correlation between light intensity and photocurrent responsivity is presented in Figure 6. The linear regression results show that changes in photocurrent responsivity are also minimal. The regression equation obtained is $-0.0000001x + 0.2149$, with a negative coefficient (-0.0000001), suggesting that photocurrent responsivity decreases as light intensity increases. However, the coefficient of determination ($R^2 = 25.98\%$) at a 60° tilt is higher than that observed at 0° and 30°, indicating that the correlation between light intensity and photocurrent responsivity is stronger at this angle. Overall, spectral photocurrent responsivity significantly affects the performance of solar cells, as it determines how efficiently the panel converts incident light into electrical energy. The spectral responsivity (SR) of a photovoltaic device reflects its sensitivity to various wavelengths of light, which directly impacts photocurrent output (Islam et al., 2022). Moreover, spectral photocurrent responsivity is also influenced by weather conditions, as variations in atmospheric conditions can alter the spectral composition of sunlight, thereby affecting the panel's overall performance (Ishii, Otani, Takashima, & Xue, 2011).

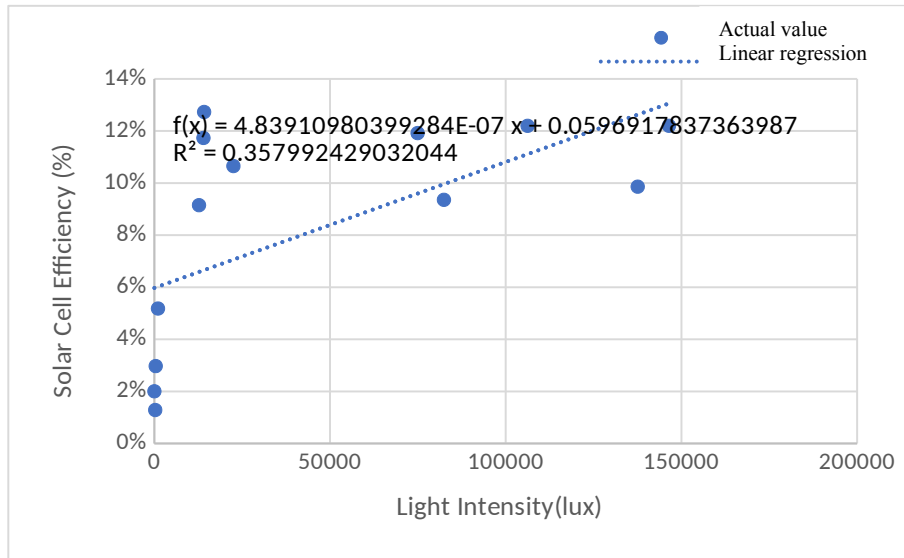


Figure 5. Variation of efficiency at a 60° tilt angle with respect to light intensity

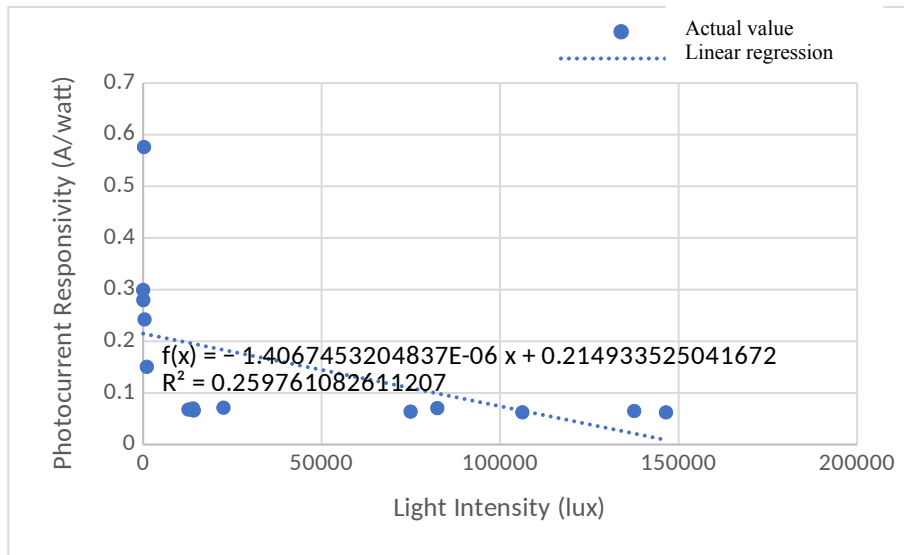


Figure 6. Variation of photocurrent responsivity at a 30° tilt angle with respect to light intensity

CONCLUSION

The correlation between light intensity and both efficiency and photocurrent responsivity of the solar panel is represented using linear regression models. The correlation analysis indicates that light intensity has a positive effect on efficiency, with the highest regression coefficient observed at $0.0000006x$ for the panel positioned at a 30° tilt angle. The coefficient of determination (R^2) at this angle is also the highest, reaching 39.19%. In contrast, the correlation between light intensity and photocurrent responsivity reveals a negative relationship, with the highest negative regression coefficient of $-0.0000001x$ occurring at a 60° tilt angle. This tilt also yields the highest R^2 value of 25.98% for photocurrent responsivity. Overall, the relationships between light intensity and both efficiency and photocurrent responsivity are relatively weak based on the linear regression models. This is likely due to the influence of other dominant factors, such as weather conditions, air humidity, and panel temperature, which significantly affect the performance of solar panels.

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