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Impact of Shading on the I-V Characteristics and Power Output of Monocrystalline and Polycrystalline Solar Panels

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Abstract – *Solar panel is a tool composed of several solar cells assembled in series or parallel by utilizing the photovoltaic effect so that it can convert solar energy into electrical energy. Solar panels have several types, namely monocrystalline and polycrystalline where each type of solar panel has different absorption efficiency based on the constituent materials. According to several surveys, obstacles that often occur in the field in the installation of solar panels are due to external influences which include influences (shading, soiling, and spot) so that it has an impact on the performance of solar panels which results in power instability due to non-linear current-voltage (I-V) relationships. This study tested the power output of monocrystalline and pollycrystalline 100 Wp solar panels with several levels of shading testing The results of testing research data that have been carried out show that there is an influence of shading on current and voltage, resulting in a decrease in output power. It was found that the partial and overall shading effects caused a decrease in power by -71% and -75% respectively from the normal conditions of monocrystalline solar panels. Polycrystalline solar panel testing due to partial shading effect of -75% and total shading of -77% of normal solar panel output power without conditioning.*

Keywords – *Characteristics I-V; Output Power; Monocrystalline; Polycrystalline; Shading.*

I. Introduction

THE rapid population growth has led to an increasing demand for electrical energy. Indonesia still relies on conventional, non-renewable energy sources such as petroleum, coal, and natural gas, whose availability is gradually depleting. Therefore, renewable alternative energy sources are necessary to address future energy crises. Indonesia, situated on the equator, enjoys high sunlight intensity [1]. It is estimated that the solar radiation intensity across Indonesia averages between 4.5-4.8 kWh/m²/day, with ideal sunlight duration averaging 4-5 hours per day for electricity production from solar panels [2].

Solar power plants harness sunlight using the photovoltaic (PV) effect to convert solar radiation into electrical energy. A range of studies have consistently shown that higher solar radiation intensity leads to increased electrical power production in photovoltaic cells. [3,4] both found that power and energy output significantly increase with higher irradiation levels. This relationship is further supported by [5], who found that solar radiation intensity is directly proportional to battery charging current. However, it is important to note that this relationship may reach a saturation point, as indicated by [4]. The influence of solar radiation intensity on the power output of photovoltaic cells is also confirmed by [6–9], but it is crucial to consider the potential limitations of solar power concentration, as highlighted by [10]. Each type of solar panel has different output power because they are made from different materials. The efficiency of monocrystalline panels ranges from 15% to 20%, made from single silicon crystals, while polycrystalline panels have an efficiency of 13% to 18%, made from silicon mixed with other materials [11].

External conditions, including varying shading effects, can cause power instability due to the non-linear relationship between current and voltage (I-V), preventing the solar panel from reaching the Maximum Power Point (MPP) [12]. Partial shading impacts the output power of solar panels, reducing the power value by 34.4% from normal conditions [13]. Shading effects on solar panels can result in a power reduction of 45.1% [14].

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Based on previous research, this study will test 100Wp monocrystalline and polycrystalline solar panels to observe their I-V characteristics and power output in response to changing environmental conditions. The testing involves shading conditions (solar panels covered by shadows), varying the shading levels to observe the effects at each level. Measurements include current (Amperes), voltage (Volts), and power (Watts) managed by a programmed microcontroller datalogger to store data on an SD card/memory, allowing analysis of the effects of each shading level on the I-V characteristics and power output of both types of solar panels. The study found that partial and full shading on monocrystalline panels caused a power output reduction of -71% and -75%, respectively, and on polycrystalline panels of -75% and -77% compared to the normal output without shading.

II. Research Methods

The method used in this research is the comparative analysis method. This method is used to facilitate researchers in comparing sample data found in the field. The research procedure is carried out by testing and comparing the two types of solar panels, monocrystalline and polycrystalline, under various shading condition levels against the I-V current-voltage characteristics and output power, and then concluding the results using a comparative approach. Data collection on both types of solar panels is carried out simultaneously in the same test conditions, with each conditioning consisting of three variations of testing levels. For example, variations in testing solar panels with shading conditions include no shading (0%), partial shading (50%), and full shading (100%).

i. Solar Panels

Solar panels consist of solar cells arranged in series or parallel. Solar cells are made from semiconductor materials called silicon. The unit in solar panels is wattpeak and is measured based on international testing standards, namely STC (Standard Test Condition), where the light intensity is $1000W/m^2$, the temperature is 25°C, and the air mass is 1.5 AM. Solar cells themselves are made from small silicon pieces coated with special chemicals and have a minimum thickness of 0.3 mm, made from semiconductor slices with positive P-type poles (photons) and negative N-type poles (electrons) [15]. Each solar cell can generate a voltage of ± 0.5 volts or only about 0.6 V without load (open circuit) or 0.45 V under load. There are two types of solar panels based on the material: monocrystalline & polycrystalline, which have different absorption efficiencies [16].

Figure 1: 100 Wp Monocrystalline and Polycrystalline Solar Panels

ii. I-V Characteristics of Solar Panels

The best performance of a solar panel is indicated by the short circuit current and open circuit voltage. This is to determine the peak power that can be achieved, so the characteristics of the solar panel can be depicted through the I-V curve or the current (I) to voltage (V) curve. The current-voltage curve is greatly influenced by the intensity of solar radiation and temperature. When the solar radiation intensity hits the surface of the solar panel, it controls the current (I), in other words, the intensity of solar radiation is directly proportional to the electrical current output. Meanwhile, temperature controls the voltage (V), the higher the surface temperature of the solar panel, the lower the voltage [17].

The I-V curve relationship shows that when the current and voltage reach the maximum power point (MPP), it results in maximum output power. The I-V curve passes through two main points, namely the short circuit current (Isc) and the open circuit voltage (Voc). The voltage at the maximum power point (Vmpp) is smaller than the open circuit voltage (Voc). Additionally, the maximum current (Impp) is also smaller than the short circuit current (Isc) [18].

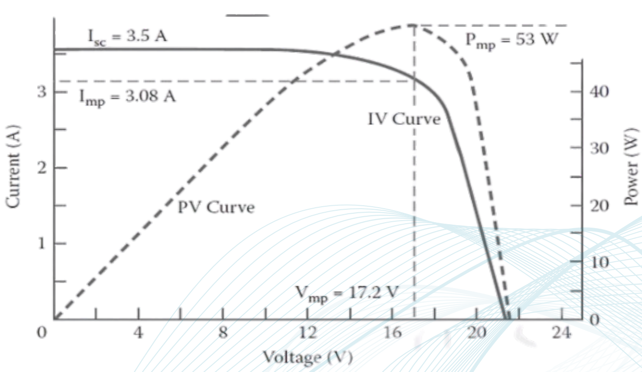

Figure 2: I-V characteristic curve at STC

iii. *Factors Affecting Solar Panel Efficiency*

Solar cells are made of semiconductor materials that can conduct electricity under various conditions but do not always make them good media for controlling electrical current. Several parameters can affect the performance of solar cells, including partial shading. Efficiency reduction is caused by gradual damage accumulation due to long-term exposure to harsh environments [19]. Below is a diagram of sources of system loss in solar panels taken from Helioscope software, which leads to less efficient solar panel performance.

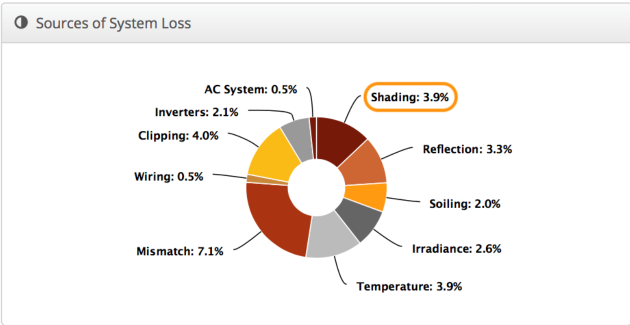

Figure 3: Sources of system loss in PV systems

According to the system loss diagram, the biggest loss affecting the performance of solar panels is caused by shading (shadowing) at 3.9%, as shadows prevent sunlight from perfectly reaching the panel surface [20].

iv. *Shading (Shadowing)*

Shading effects are the potential obstructions on solar panels caused by shadows of objects, which reduce the amount of solar radiation received by the cells. When shading occurs, the shaded solar cells turn into passive loads and behave like diodes in a blocking condition, preventing current produced by other functioning cells. The solar panel circuit consists of solar cells connected in series to produce the desired power. One silicon cell produces 0.46 Volts, so 23 cells form a 12 Volt solar panel, and 36 series-connected silicon cells result in 0.46 Volts x 36 = 16.56 Volts. Thus, even a small shadow covering the solar panel surface, such as a branch, can significantly reduce power output [21].

Shading significantly affects the current because solar irradiation does not perfectly illuminate the solar panel surface. Below is a table showing the significant impact of shading on the output power of single crystalline solar panels without internal bypass diodes [22].

To determine the area of the solar panel exposed to sunlight, we can use equation (1):

$$A_p = \frac{Pout}{Pmax} \times 100\% \tag{1}$$

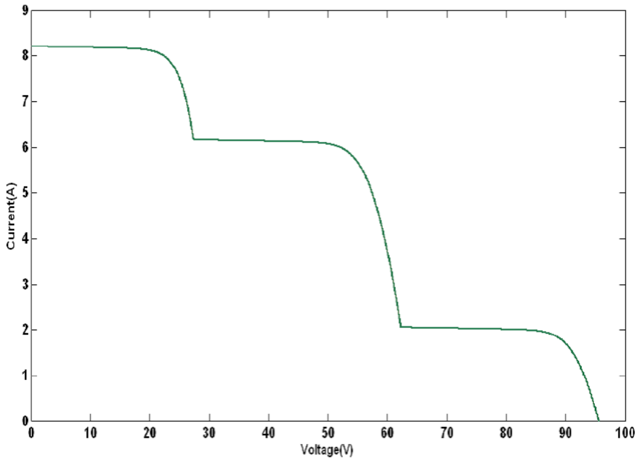

Figure 4: Effect of partial shading on solar panels

Table 1: Impact of shading on solar panel output power

shading	Percentage loss
0%	0%
25%	55%
50%	50%
75%	66%
100%	75%
3 cells shaded	93%

In the calculation of the effect of shading on solar panels, A_p represents the percentage of the solar panel area exposed to sunlight (%), *Pout* is the output power (Watt), and *Pmax* is the maximum power point (MPP) from solar panel specifications (Watt).

After obtaining the area of the solar panel exposed to sunlight, we can calculate the effect of shading using equation (2):

$$\text{Effect shading} = 100\% - A_p \tag{2}$$

with: A_p is a percentage of the solar panel area exposed to sunlight (%)

v. *System Design*

In this research, the system created has several working steps that can be understood through the block diagram in Figure 5.

In Figure 5, the first process is explained by conditioning the monocrystalline and polycrystalline solar panels to be affected by shading by simulating shadows on the solar panel surface using plywood to cover the top of the panel with three testing levels: no shading (0%), partial shading (50%), and full shading (100%). The output from the solar panels is connected to data acquisition equipment. The data acquisition equipment will collect data on temperature, irradiation, voltage,

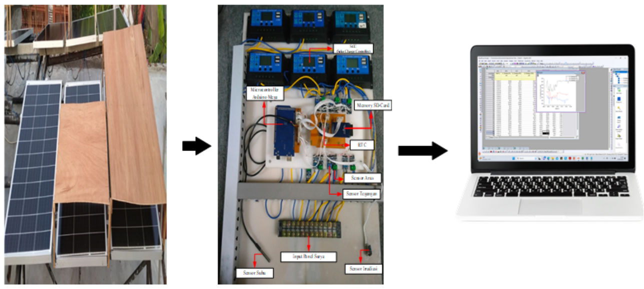

Figure 5: System block diagram

current, and power through sensors managed by a programmed microcontroller datalogger so that the data read can be stored in an SD card/memory. The data is then exported to Excel to observe the effects of each shading test level on the I-V characteristics and output power of the two types of solar panels. In this study, three levels of shading test conditions were created to observe the impact of shading level on I-V characteristics and output power. Figure 6 illustrates the shading conditions used in this study. For 50% shading conditions, the surface of the solar panel is partially covered horizontally.

Figure 6: Solar panel shading test conditions

III. Results and Discussion

In this study, data collection was conducted in Sidoarjo City, Taman Subdistrict, Wage Village, specifically on Ratuayu Street, Punden II alley. To test each shading condition, consistent solar irradiation is needed to observe the current-voltage characteristics. The researcher collected solar irradiation data from 11:00 AM to 1:00 PM. Table 2 shows the daily solar irradiation measurement data.

Based on Table 2, the solar irradiation data collected over 6 days show that solar irradiation from 11:00 AM to 1:00 PM averages consistently around 1000 W/m², indicating that the solar panel shading tests will be conducted during these hours to maintain consistent solar irradiation conditions.

Based on Table 3, the average voltage, current, and power output from the monocrystalline solar panel shows that the average values for each shading condition differ due to the shading conditions of 50% and 100% causing parts of the solar panel to be covered by shadows, thus preventing the irradiation from fully illuminating the panel surface. According to the principle of solar panel operation, irradiation significantly affects the output current, thereby impacting the power output generated by the solar panel.

Table 2: Daily Solar Irradiation Measurement Data

Time	Solar Irradiation Measurement Data (W/m²)					
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
11:00	990.3	936.5	1050.2	1130.4	1012.3	990.1
11:05	857.5	903.5	1085.3	1134.3	1028.6	978.9
11:10	1008.6	945.3	1113.3	1136.7	1056.8	1001
11:15	1132.4	933.9	1017.1	1091.2	941.2	1018.3
11:20	1161.8	989.5	1086.1	1125.6	990.4	1003.2
11:25	882.8	937.7	1014.7	1065.5	1064.8	1025.8
11:30	1016.5	997.4	1051.1	1064.2	928.1	1020.1
11:35	994	1099.1	1032	1054.8	930.2	1034.7
11:40	1086.5	1020.3	1020.1	1045.4	1077.3	1042.4
11:45	1075.5	999.9	1031	1002.8	1018.3	1059.8
11:50	1065.5	995.9	1026.6	1052.8	1030.8	1052
11:55	1070.75	1054.5	1032.6	1053.6	1017.7	1115
12:00	1076.5	1053.7	1026.8	1045.4	1007.7	1058
12:05	1064.3	1015.3	1023.3	1033	1015.7	1022.7
12:10	1052.1	1049.9	1017.4	1038	980.3	1045.6
12:15	1059.45	1057.2	1019.6	1094.9	1015.7	1022.5
12:20	1066.8	1046.3	1024.4	1057.7	1011.4	1012
12:25	1065.5	1041.8	1011.8	1048.5	1011.4	1014.6
12:30	1064.2	1050.8	1002.6	1040.7	1008.2	1025
12:35	1054.8	1044.9	1019.1	1087.4	1011.5	967.5
12:40	1045.4	1031	1006.3	1086.2	1000	971
12:45	1002.8	1002.5	1021.8	768	1001.2	976.5
12:50	1052.8	1028.4	1035.4	698	1017.3	969.5
12:55	1053.6	1115.7	1019.5	593.3	1009.4	950.1
13:00	1045.4	1025.6	978.2	561.5	1001.2	968.7
Average	1041.83	1015.06	1030.65	1004.40	1007.50	1013.80

Table 3: Shading Test Data for Monocrystalline Solar Panel

Time	Shading (0%)			Shading (50%)			Shading (100%)		
	V	I	P	V	I	P	V	I	P
11:00	21.31	4.17	88.86	20.24	1.44	29.15	19.91	1.22	24.29
11:05	22.00	5.13	112.86	20.33	1.64	33.34	19.92	1.25	24.90
11:10	21.37	4.89	104.50	20.23	1.43	28.93	19.92	1.09	21.71
11:15	21.26	5.14	109.28	19.99	1.45	28.99	19.96	1.29	25.75
11:20	21.18	5.10	108.02	20.12	1.49	29.98	19.88	1.29	25.65
11:25	22.00	5.20	114.40	20.09	1.50	30.14	19.87	1.26	25.04
11:30	21.78	4.12	89.73	20.05	1.51	30.28	19.90	1.26	25.07
11:35	22.10	4.37	96.58	20.26	1.53	31.00	19.93	1.27	25.31
11:40	21.67	4.27	92.53	20.35	1.49	30.32	20.00	1.30	26.00
11:45	21.88	4.16	91.02	20.27	1.47	29.80	19.95	1.32	26.33
11:50	21.79	4.53	98.71	20.15	1.48	29.82	19.88	1.33	26.44
11:55	22.00	4.35	95.70	20.21	1.51	30.52	19.95	1.31	26.13
12:00	22.61	4.97	112.37	20.77	1.47	30.53	19.83	1.24	24.59
12:05	22.56	5.20	117.31	20.55	1.40	28.77	19.62	1.23	24.13
12:10	22.56	4.85	109.42	20.67	1.53	31.63	19.66	1.34	26.34
12:15	22.59	4.77	107.75	20.66	1.47	30.37	19.63	1.29	25.32
12:20	22.69	5.06	114.81	20.70	1.47	30.43	19.67	1.26	24.78
12:25	22.67	4.53	102.70	20.75	1.48	30.71	19.69	1.31	25.79
12:30	22.70	4.38	99.43	20.79	1.47	30.56	19.71	1.29	25.43
12:35	22.53	4.33	97.55	20.81	1.50	31.22	19.68	1.33	26.17
12:40	22.64	4.51	102.11	20.83	1.49	31.04	19.71	1.32	26.02
12:45	22.64	4.79	108.45	20.71	1.51	31.27	19.64	1.33	26.12
12:50	22.71	4.67	106.06	20.74	1.36	28.21	19.63	1.34	26.30
12:55	22.52	4.96	111.70	20.66	1.56	32.23	19.57	1.43	27.99
13:00	22.62	4.92	111.29	20.60	1.33	27.40	19.57	1.37	26.81
Average	22.18	4.69	104.13	20.46	1.48	30.26	19.79	1.29	25.54

Based on Table 4, the average voltage, current, and power output from the polycrystalline solar panel during the shading tests of 50% and 100% caused a decrease in current due to the theory that the principle of solar panel operation is highly influenced by irradiation, which affects the output current and subsequently impacts the power output generated by the solar panel. The results of the shading tests with varying conditioning levels for both types of solar panels in terms of voltage, current, and power output are shown in Figures 7 to 8. The black graph represents the test on the mono solar panel without shading, the red graph represents the test on the mono solar panel with partial shading (50%), the blue graph represents the test on the mono solar panel with full shading (100%), the green graph represents the test on the poly solar panel without shading, the purple graph represents the test on the poly solar panel with partial shading (50%), and the gold graph represents the test on the poly solar panel with full shading (100%).

Table 4: Shading Test Data for Polycrystalline Solar Panel

Time	Shading (0%)			Shading (50%)			Shading (100%)		
	V	I	P	V	I	P	V	I	P
11:00	19.21	5.46	104.89	19.39	1.40	27.15	18.30	1.22	22.33
11:05	20.35	5.27	107.24	19.43	1.45	28.17	18.40	1.19	21.90
11:10	20.11	5.90	118.65	19.41	1.40	27.17	18.39	1.19	21.88
11:15	19.91	5.44	108.31	19.50	1.38	26.91	18.36	1.17	21.48
11:20	19.26	5.47	105.35	19.29	1.51	29.13	18.46	1.17	21.60
11:25	19.18	5.46	104.72	19.45	1.39	27.04	18.30	1.13	20.68
11:30	19.21	5.11	98.16	19.41	1.42	27.56	18.22	1.22	22.23
11:35	19.99	5.45	108.95	19.42	1.35	26.22	18.47	1.22	22.53
11:40	20.05	5.40	108.27	19.44	1.44	27.99	18.39	1.19	21.88
11:45	19.96	4.99	99.60	19.47	1.51	29.40	18.15	1.23	22.32
11:50	20.00	4.95	99.00	19.21	1.53	29.39	18.39	1.25	22.99
11:55	19.95	5.10	101.75	19.30	1.49	28.76	18.15	1.27	23.05
12:00	19.98	5.16	103.10	19.47	1.41	27.45	18.49	1.21	22.37
12:05	19.91	5.40	107.51	19.38	1.53	29.65	18.36	1.20	22.03
12:10	19.89	5.23	104.02	19.40	1.55	30.07	18.34	1.59	29.16
12:15	19.98	5.12	102.30	19.42	1.60	31.07	18.34	1.10	20.17
12:20	20.05	5.37	107.67	19.49	1.65	32.16	18.10	1.25	22.63
12:25	19.98	4.95	98.90	19.39	1.61	31.22	18.15	1.27	23.05
12:30	20.00	4.78	95.60	19.41	1.62	31.44	18.21	1.29	23.49
12:35	20.09	4.77	95.83	19.40	1.59	30.85	18.22	1.30	23.69
12:40	20.15	4.72	95.11	19.43	1.60	31.09	18.25	1.28	23.36
12:45	20.16	4.71	94.95	19.50	1.64	31.98	18.40	1.34	24.66
12:50	20.05	4.90	98.25	19.52	1.60	31.23	18.44	1.40	25.82
12:55	20.02	4.93	98.70	19.49	1.68	32.74	18.33	1.45	26.58
13:00	20.06	4.87	97.69	19.51	1.58	30.83	18.43	1.46	26.91
Average	19.90	5.16	102.58	19.42	1.52	29.47	18.32	1.26	23.15

The graph in Figure 7 shows the comparison of monocrystalline and polycrystalline solar panels when exposed to shading effects on the voltage side. The voltage of the solar panels was recorded every 5 minutes. The graph in Figure 7 shows that solar panels without shading produce an average voltage of 22.18 volts for monocrystalline and 19.90 volts for polycrystalline. However, when partially and fully shaded, the monocrystalline panels produce an average voltage of 20.46 volts and 19.79 volts, respectively, while the polycrystalline panels produce an average voltage of 19.42

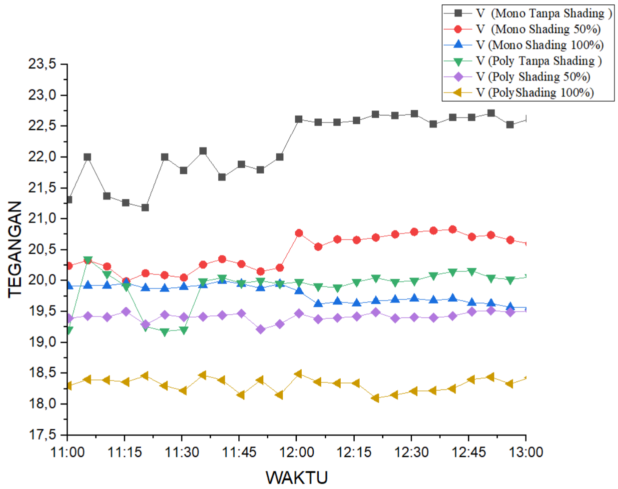

Figure 7: Voltage Comparison Data for Solar Panels

volts and 18.32 volts, respectively.

The output current of the solar panels was also measured and compared. The current measurement data is shown in Figure 8.

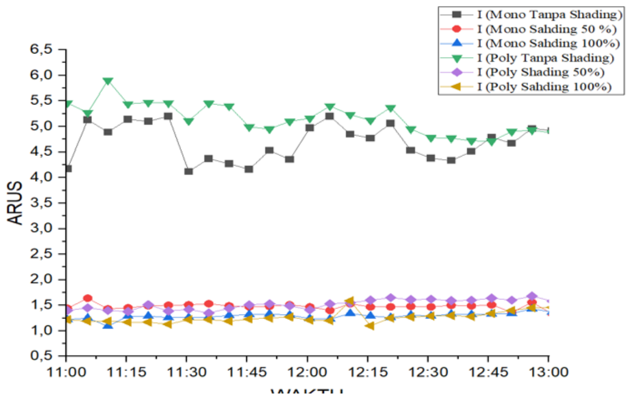

Figure 8: Current Comparison Data for Solar Panels

The graph in Figure 8 compares the monocrystalline and polycrystalline solar panels when exposed to shading effects on the current side, recorded every 5 minutes. The output current of the shaded solar panels shows a significant decrease compared to normal, unshaded panels. This is because shaded panels do not receive full solar irradiation on their surface. According to the theory of solar panel operation, the less solar irradiation received by the panel, the lower the current produced. The graph in Figure 8 shows that partially and fully shaded monocrystalline panels produce an average current of only 1.48 A and 1.29 A, respectively, while polycrystalline panels produce only 1.52 A and 1.26 A, respectively. This is far from the average current of unshaded monocrystalline panels 4.69 A and polycrystalline panels 5.16 A.

The electrical power is obtained from the multiplication of the output current and voltage of the solar panels and then compared. The electrical power produced in this test is shown in the graph in Figure 9.

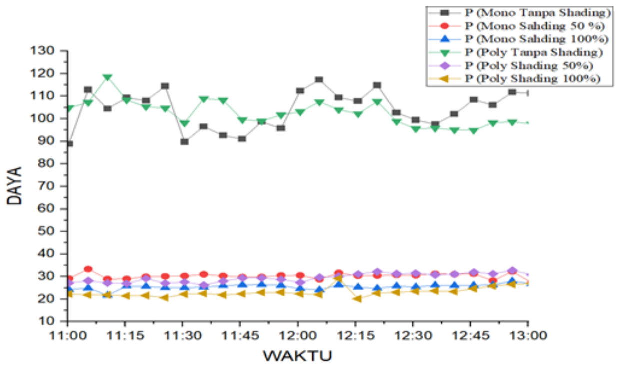

Figure 9: Power Comparison Data for Solar Panels

The graph in Figure 9 shows the comparison of monocrystalline and polycrystalline solar panels when exposed to shading effects on the output power side, recorded every 5 minutes. The graph in Figure 9 explains that the output power of solar panels is related to voltage and current; when the current produced is small, the output power will also be small compared to the output power of normal, unshaded solar panels. The graph in Figure 9 shows that unshaded solar panels produce an average output power of 104.13 watts for monocrystalline and 102.58 watts for polycrystalline. However, when partially and fully shaded, the monocrystalline panels produce average output power of 30.26 watts and 25.54 watts, respectively, while the polycrystalline panels produce average output power of 29.47 watts and 23.15 watts, respectively.

Based on Figures 7 to 9, the comparison data of voltage, current, and output power of monocrystalline and polycrystalline solar panels when exposed to shading effects with varying levels of conditioning show that shading significantly affects the current output. The average results are shown in Table 4.

Table 5: Comparison of Solar Panels under Different Shading Conditions

Type of Solar Panel	Test Condition								
	Normal			Shading 50%			Shading 100%		
	V	I	P	V	I	P	V	I	P
Monocrystalline	22.18	4.69	104.13	20.46	1.48	30.26	19.79	1.29	25.54
Polycrystalline	19.90	5.16	102.58	19.42	1.52	29.47	18.32	1.26	23.15

Table 5 shows the average comparison data of voltage, current, and output power of monocrystalline and polycrystalline solar panels affected by shading. The comparison shows that shading causes a significant decrease in current, with an average decrease of up to 1-2 amperes, which impacts the output power produced.

To determine the percentage of voltage, current, and output power losses caused by shading, we can compare the average results of unconditioned solar panels with the average results of shading-conditioned solar panels. The percentage reduction calculation is shown in Table 6.

$$\Delta(\%) = \left(\frac{A_n - A_t}{A_n}\right) \times 100\%$$

with: $\Delta(\%)$ = Percentage Reduction, A_n = Average value without treatment, A_t = Average value with treatment applied.

Table 6: Percentage Reduction Due to Shading

Conditioning	Percentage Reduction (%)					
	Monocrystalline			Polycrystalline		
	Voltage	Current	Power	Voltage	Current	Power
Shading 50%	-8%	-68%	-71%	-2%	-71%	-75%
Shading 100%	-11%	-73%	-75%	-8%	-75%	-77%

The calculation results in Table 6 show the percentage reduction due to shading, indicating that polycrystalline solar panels can still maintain voltage with a decrease of only -2% and -8% compared to monocrystalline solar panels. However, polycrystalline panels experience a significant decrease in current by -71% to -75%. The shading effects of partial and full shading cause a reduction in output power by -75% and -77%, respectively, for polycrystalline panels, and -71% and -75% for monocrystalline panels. Table 5 and Table 6 show that monocrystalline solar panels still perform better under shading, with higher output power compared to polycrystalline panels.

IV. Conclusion

The results of testing 100 Wp monocrystalline and polycrystalline solar panels under shading effects show that partial and full shading causes a decrease in output power. Monocrystalline panels experience a power reduction of -71% and -75%, while polycrystalline panels experience a reduction of -75% and -77% compared to normal, unconditioned solar panels. This decrease in output power is caused by a reduction in the output current of the solar panels due to the shading effect, which prevents the solar cells from receiving full irradiation. According to the theory of solar panel operation, the lower the irradiation received by the solar panel, the lower the current produced. In this test, shading was simulated by covering the surface of the solar panels with plywood to create the shading effect. The test results show that monocrystalline solar panels perform better under shading, with higher output power compared to polycrystalline panels. Future research is expected to include more variations in shading conditions on the surface of the solar panels to obtain more accurate results for both types of solar panels under shading effects.

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