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Performance Analysis of On-Grid Solar Power Plant under Various Irradiation and Load Condition

Andarini Asri[1,a] , Annisa [2,b], Ruslan L[3,b]
[1,2,3] Jurusan Teknik Elektro, Politeknik Negeri Ujung Pandang
[a] andariniasri@poliupg.ac.id,
[b]tahirannisa4@gmail.com,
[c] ruslanlausu@gmail.com

Abstract-This research aims to analyze the effect of irradiation and load variations on the performance of the 1 kWp on-grid solar power plant at Ujung Pandang State Polytechnic. The research was conducted for 7 days with component testing on May 8, 2024, irradiation variation testing on May 15-17 and June 5-6, 2024, and load variation testing on June 8, 2024. MATLAB GUI was used to theoretically calculate power, PV and GTI efficiency, Yf, Yr, PR, apparent power, and load reactive power. In addition, the MATLAB GUI also displays graphs of the effect of irradiation variations on the performance of solar power plants. PSIM simulation was used to compare the PV power generated with the same irradiation and temperature. The results show that irradiation greatly affects the performance of the solar power plant, where increasing irradiation increases the output power, PV and GTI efficiency, and export power to the grid, which results in an increase in Yf, Yr, and PR. PSIM simulations support these findings by showing a positive correlation between irradiation and PV output power. Load variation also affects the Pf value, where resistive (R) loads have the best Pf (1), while inductive-capacitive (LC) loads have the worst Pf (0.37) due to the high reactive power drawn. Thus, variations in load type affect power consumption and system performance.

Keywords: on-grid solar power plant, irradiation, RLC load, PV efficiency, GTI efficiency, solar power plant performance

I. Introduction

Solar Power Plant is a power plant that uses solar energy into its primary energy which is then used as electrical energy using PV (photovoltaic) [1]. The power generated by solar power plant is influenced by various factors, including solar radiation found at the solar power plant location, the slope and direction of the solar panel, the presence or absence of sunlight, the temperature of the area at the solar power plant location, and the technical performance of the components used [2]. PLTS performance is greatly influenced by irradiation conditions (solar radiation received per unit area) and the connected electrical load. Understanding how solar PV works under these various conditions is important to ensure energy efficiency and optimal system management [3].

The problems caused by irradiation variations are output drop at low irradiation, system oversizing at high irradiation, instantaneous power fluctuations. Meanwhile, the problem caused by the variation of the Pf value load varies [4]. From the problems caused by irradiation variations and loads, research is needed to determine the irradiation factors and loads on on-grid solar power plants.

Research in the journal Engineering Science and Applications “Reliability Analysis of Grid Tied Inverter (GTI) Systems on-grid Solar PV 9x80 WP” with the results of his research stating that when the value of solar radiation is low, the efficiency value of the Grid Tied Inverter is also low, when the radiation value starts to increase, the efficiency value of the Grid Tie Inverter is getting higher and more consistent[5]. In addition to load irradiation also affects the performance of solar power plants. Journal of New and Renewable Energy “Effect of RLC Load on 100WP On Grid Solar Power Plant” with the results of his research load variations cause variations in the value of the power factor in solar power plant [6].

PNUP has a solar power plant simulator which is the result of cooperation between PT PJB and PNUP. In the solar power plant simulator practicum, the practicum carried out is only the practicum of solar panel configuration and on-grid solar power plant performance. The simulator has not yet conducted research on the performance of on-grid solar power plant at various load variations and irradiation variations. Therefore, it is necessary to conduct research to determine the performance of on-grid solar power plant in various irradiation and load conditions on the PNUP on-grid solar power plant simulator.

Based on this description, the authors are interested in examining the performance of on-grid solar power plant which is influenced by variations in irradiation and load. The title raised is “Analysis of On-Grid solar power plant Performance in various Irradiation and Load Conditions”.

II. Research Methodology

A. Place and Time of Research

Research on the performance of on-grid *solar power plant* at various irradiation and load conditions on the *solar power plant* simulator in the power generation laboratory, electrical building, PNUP campus 2, Moncongloe, Makassar. Data collection was carried out from 09.00 to 15.00 WITA.

Data collection of solar power component testing which includes testing solar panels and GTI was carried out on May 8, 2024. Data collection for testing the effect of irradiation on the performance of solar power was carried out on May 15-17 and June 05-06, 2024. Data collection of load variation testing on the performance of solar power was carried out on June 07, 2024. After data collection, data processing was carried out on June 08-15, 2024.

B. Research Procedures

The procedure for this activity can be carried out in a structured and systematic manner to make it easier to carry out and direct, the following steps are taken:

1. literature study
2. Observation which includes collecting data on PV and GTI specifications, assembling the simulator, taking measurements, GUI modeling, and PSIM modeling.
3. Interview
4. Data identification
5. Data analysis which includes analyzing the performance of solar power plant under various irradiation conditions (PV and GTI output, PV and GTI efficiency, Yr, Yf, PR, and energy export) and analyzing the performance of solar power plant under various loads (Pf, S, and Q).

The steps and methods for this activity are depicted in Figure 1, the activity procedure flowchart below.

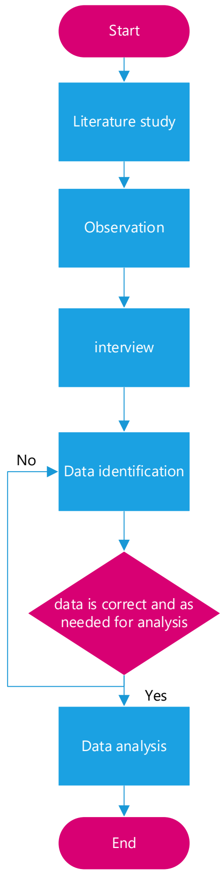


Figure 1 Activity Procedure Flowchart

C. Data Collection Techniques

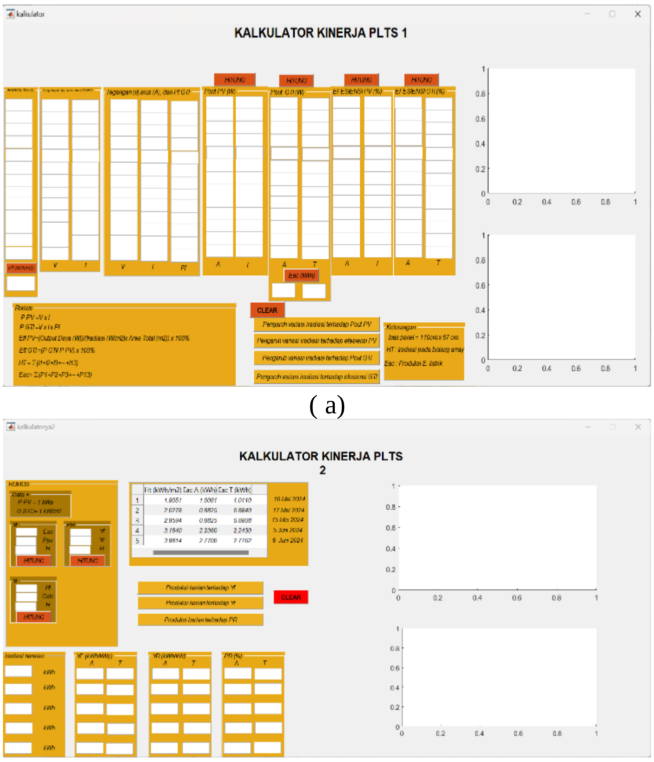
The data collection method used in this research is as follows.

1. Literature
2. Observation
3. Interview
4. Laboratory experiments which include simulation of solar power plant component testing, simulation of solar power plant performance testing against irradiation variations, and simulation of solar power plant performance testing against load variations.

D. Analysis Techniques

1. performance analysis of solar power plants under various irradiation conditions

This analysis uses irradiation testing data on solar panel output power, irradiation testing on GTI output power, and grid export and import energy data, the data is then processed by doing theoretical calculations with GUI. GUI calculator can be seen in Figure 2.



(a)

(b)

Figure 2 GUI calculator display, (a) solar power plant performance with irradiation variation, (b) solar power plant performance

The parameters calculated are:

a. Output power of PV

To get the value of PV output power, you can use the formula:

$$Pout\ PV = V \times I \quad (1)[7]$$

b. Output power of GTI

To get the value of the GTI output power, you can use the formula:

$$GTI\ output\ power = V \times I \times \cos\phi \quad (2)$$

Description:

Pout GTI : GTI output power (W)

V : GTI voltage (V)

I : GTI current (I)

c. PV efficiency

To obtain the efficiency value of PV, you can use the following formula:

$$\eta PV = (Pout\ PV)/(Irradiation \times A) \quad (3)[8]$$

Description:

ηPV : PV efficiency (%)

Pout PV : PV output power (W)

A : panel surface area (m^2)

Irradiation : Irradiation (W/m^2)

d. GTI efficiency

GTI efficiency can be calculated by the formula:

$$\eta GTI = (Vout \times Iout)/(Vin \times Iin) = Pout/Pin \quad (4)\ [9]$$

Description:

ηGTI : GTI efficiency (%)

Vout : GTI voltage (V)

Iout : GTI current (A)

Vin : PV voltage (V)

Iin : PV current (A)

e. Yiel Factor (Yf)

Yield Factor (Yf) is a measure of the efficiency of a photovoltaic (PV) system in producing electrical energy over a given period.

$$Yf = E_{AC}/P_{PV} \quad (5)\ [10]$$

Description

Yf : Yield Factor (kWh/kWp)

E_{AC} : electrical energy production (kWh AC)

P_{PV} : solar power plant power capacity (kWp DC)

f. Yield Reference (Yr)

Reference Yield (Yr) is a theoretical measure of the energy expected to be produced by a photovoltaic (PV) system based on the intensity of solar radiation received by the panels over a given periodReference Yield (Yr) can be calculated using the formula:

$$Y_r = H_T/G_{STC} \quad (7)$$

Description

Yr : Yield Reference (kWh/kW)

HT : irradiation in the array plane (kWh/m2)
GSTC : STC reference irradiation (1kW/m2)
I: Irradiation

g. Performance Ratio (PR)

The performance ratio (PR) is a measure of the efficiency of a photovoltaic (PV) system that shows how well the system converts solar radiation into electrical energy compared to the maximum potential produced. The performance ratio (PR) can be calculated using the formula:

PR= Y_f/Y_r x 100%……….(9) [11]

Description
PR : Performance Ratio (%)
Yf : Yield Factor (Kwh/kWp)
Yr : Reference Yield (kWh/kW)

In addition, PSIM simulations are also carried out and compared with actual data. PSIM circuit can be seen in figure 3.

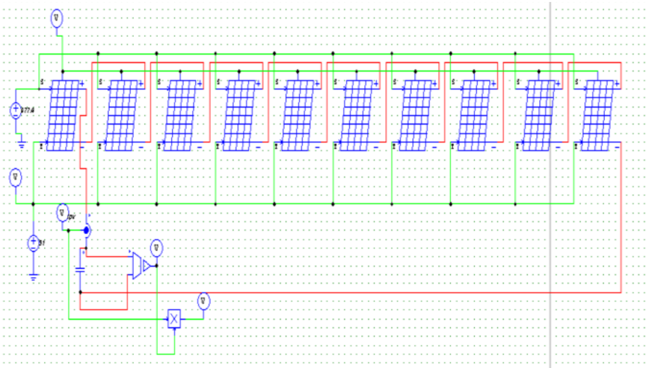


Figure 3 Solar power simulation with PSIM

2. performance analysis of solar power plants under various irradiation conditions

This analysis uses load variation test data on the performance of solar power plant, the data is then processed by doing theoretical calculations. After doing the calculation, the effect of load variation on apparent power, reactive power, and Pf is analyzed. GUI display can be seen in Figure 4.

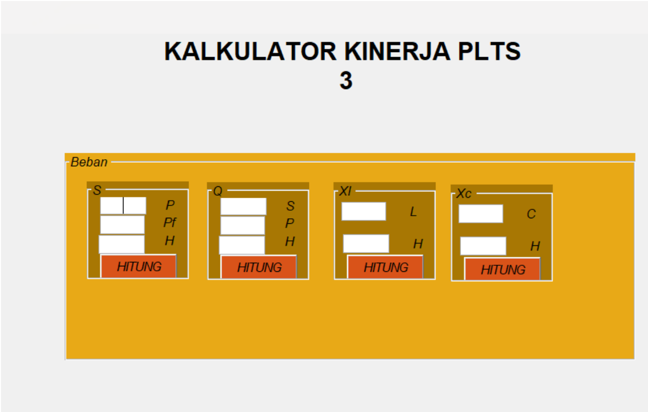


Figure 4 calculation of solar power plant performance with load variation.

The parameters calculated are:

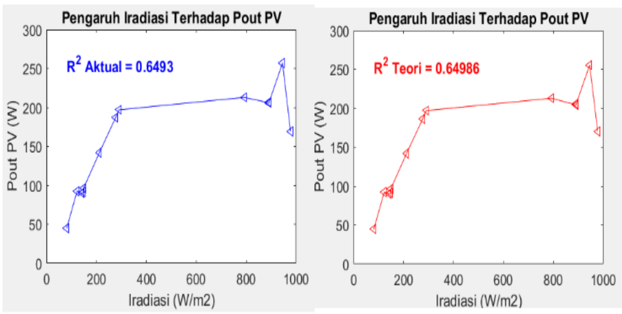
$$S = P/Pf \quad \ldots\ldots\ldots\ldots\ldots (10)$$
$$Q = \sqrt{(S^2 - P^2)} \ldots\ldots\ldots\ldots\ldots (11)$$

III. Results and Discussion

A. Effect of Irradiation Variation on on Solar Power Plant Performance

1. Effect of irradiation variation on PV output power

In this study, a comparison of PV output results from experimental results on the solar power plant simulator, GUI calculation results, and PSIM simulation results was carried out.



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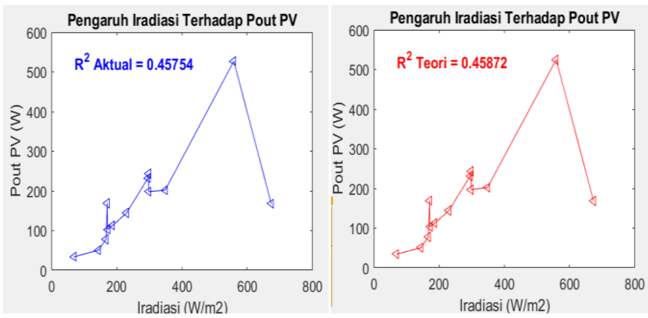

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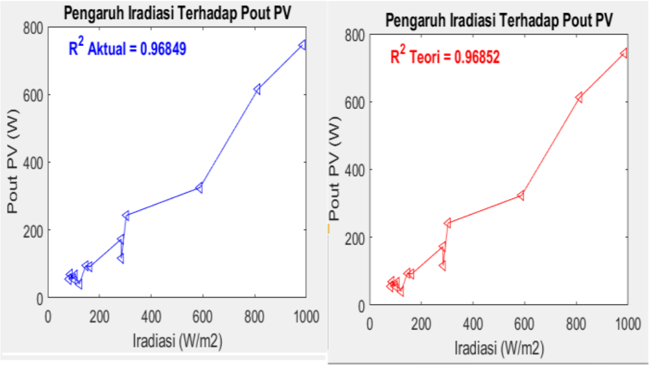

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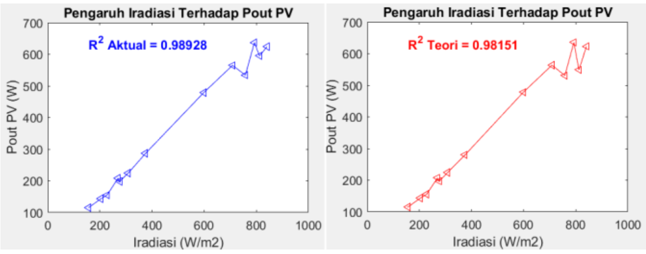

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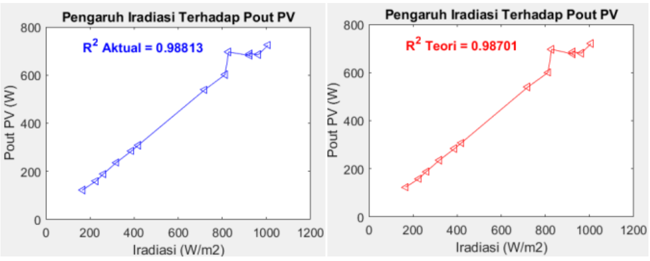


(e)

Figure 5 Effect of irradiation variation on PV output power, (a) day-1, (b) day-2, (c) day-3, (d) day-4, and (e) day-5

Table 1 Effect of irradiation variation on PV output power by PSIM

Time	Temperature (°C)	Irradiation (W/m²)	Power PV PSIM (W)
		Day-1	
09.00	31	791,9	223,02
09.30	31	945,1	249,76
10.00	31	977,4	171,66
10.30	31	891,6	210,12
11.00	31	891,2	221,78
11.30	31	290,5	184,59
12.00	31	276,8	187,97
12.30	31	81	-

Time	Temperature (°C)	Irradiation (W/m²)	Power PV PSIM (W)
13.00	31	141,4	84,91
13.30	31	148,3	92,38
14.00	31	211,9	142
14.30	31	149,1	93,36
15.00	31	122,7	-
		Day-2	
09.00	28	171,1	-
09.30	28	295,2	232,95
10.00	28	558,7	547,44
10.30	31	348,3	202,69
11.00	31	297,2	225,12
11.30	31	69,5	-
12.00	31	673,3	171,01
12.30	31	298	193,41
13.00	31	229,8	144,01
13.30	31	187,1	113,01
14.00	32	171,5	103,06
14.30	32	166,7	77,54
15.00	32	143,8	50,503
		Day-3	
09.00	29	587,8	355,41
09.30	29	812,3	634,54
10.00	29	985,1	796,23
10.30	29	283,4	163,003
11.00	32	303,3	251,72
11.30	32	284	116,1
12.00	32	121,5	40,3
12.30	32	97,2	-
13.00	32	80,6	50,11
13.30	32	106,1	-
14.00	32	162,5	92,005
14.30	32	145,9	91,63
15.00	32	85,8	-
		Day-4	
09.00	29	758	534,34
09.30	29	598,6	493,64
10.00	29	841,1	670,32
10.30	30	227,7	155,01
11.00	30	308,4	234,01

Time	Temperature (°C)	Irradiation (W/m^2)	Power PV PSIM (W)
11.30	30	203,6	143,007
12.00	30	269,6	208,005
12.30	31	792,7	650,04
13.00	29	375,5	287,08
13.30	29	275,8	197,8
14.00	29	812	595,4
14.30	30	708,6	565,48
15.00	31	156,4	105,1
		Day-5	
09.00	29	720,2	555,67
09.30	29	812,3	615,95
10.00	29	388,4	285,16
10.30	29	419,1	310,88
11.00	29	1008	785,76
11.30	31	828,6	744,79
12.00	32	925	733
12.30	32	962,7	749,54
13.00	32	226,4	159,02
13.30	32	319,7	237,006
14.00	32	925,4	706,7
14.30	32	166,5	119,57
15.00	31	260,6	189,007

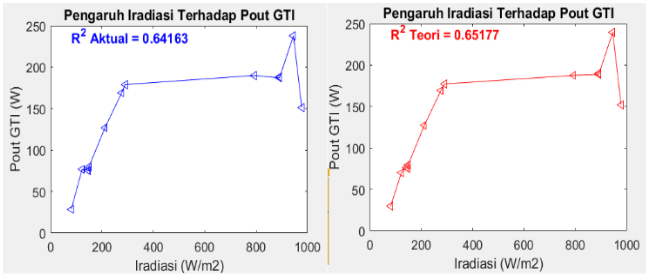
Figure 5 and table 1 are the PV output from the solar power simulator simulation, GUI calculation, and PSIM simulation for 5 days. Based on the three figures, the higher the irradiation, the higher the PV power generated. However, the power generated, in addition to irradiation, is also influenced by other factors such as shadow effects and weather. This condition has been previously revealed in previous research conducted by Mochammad Iedvan Maulana (2021) which states that the higher the solar intensity, the higher the output power produced.

PV output power based on GUI calculations explains the increase in output power along with increasing irradiation. with the percentage error with the largest actual data is 8.44% which is due to the power measuring instrument on the solar power plant simulator is less accurate but still within the measurement tolerance limit.

PSIM simulation shows the same phenomenon with the largest percentage error with actual data is 9.42%.

2. Effect of Irradiation Variation on GTI Output Power

In this study, a comparison of GTI output results from experimental results on the solar power simulator and the results of GUI calculations was carried out.



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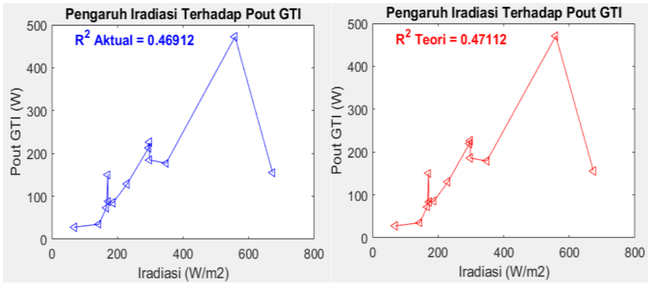

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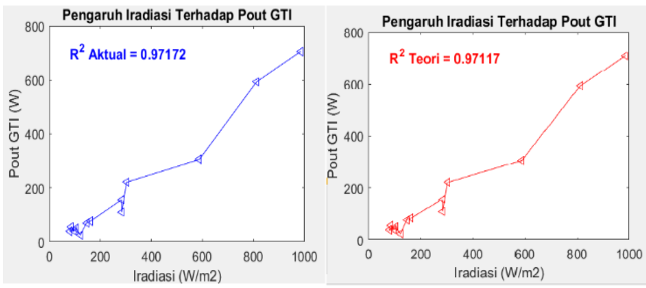

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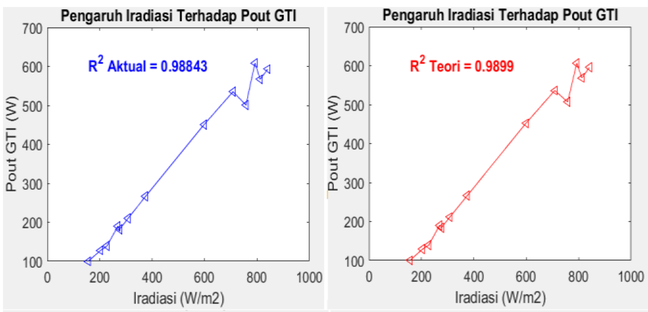

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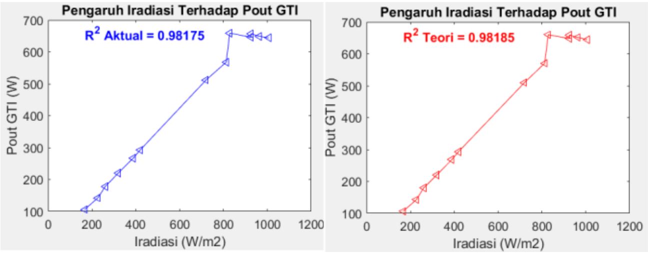


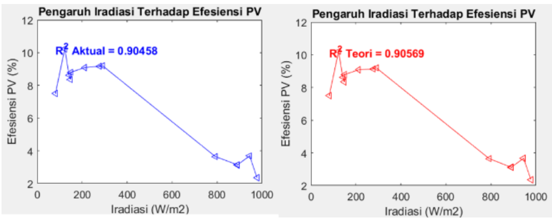
(e)

Figure 6 Effect of irradiation variation on GTI output power (a) day-1, (b) day-2, (c) day-3, (d) day-4, and (e) day-5

Figure 6 is a graph displaying the effect of irradiation variation on GTI output power. Based on the figure, it shows that the GTI power increases as the irradiation increases. After doing theoretical calculations with the GUI, it shows the same phenomenon with the largest percentage error with actual data is 9.44% which occurs because the power measuring instrument on the simulator is less accurate but still within the tolerance limits of the measuring instrument [12].

3. Effect of irradiation variation on PV efficiency

In this study, a comparison of PV efficiency from experimental results on a solar power simulator and GUI calculation results was carried out.



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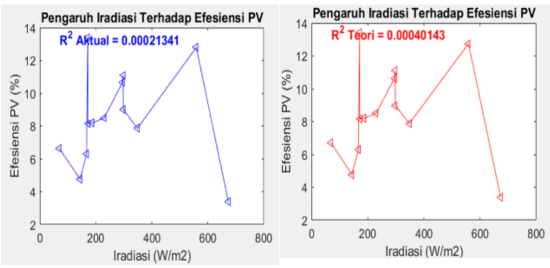

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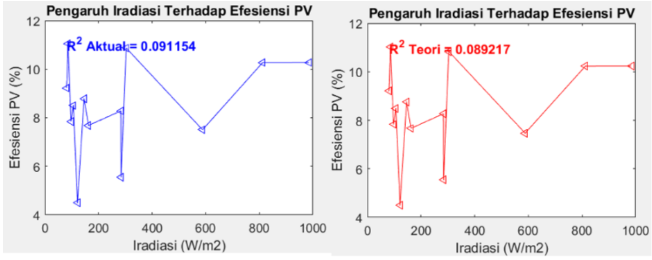

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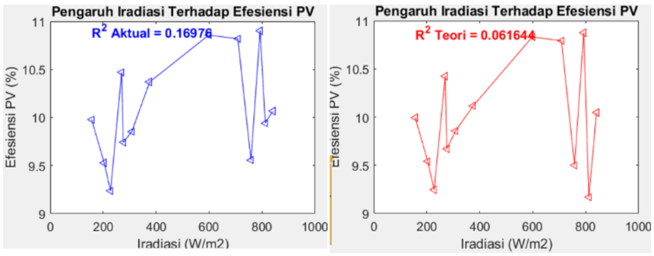

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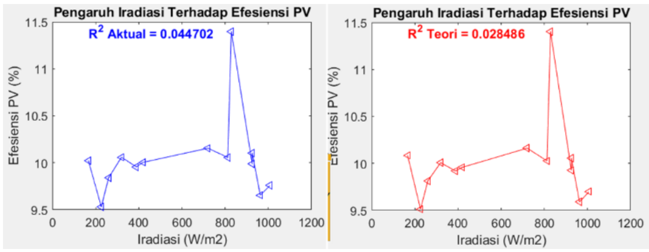


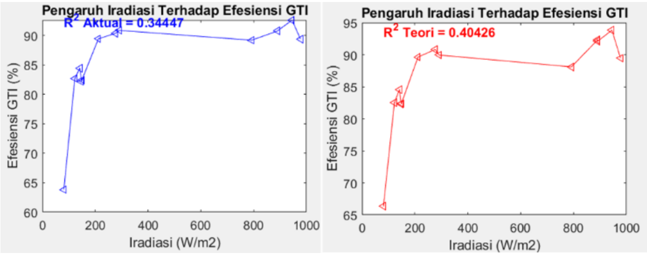
(e)

Figure 7 Effect of irradiation variation on PV efficiency Effect of irradiation variation on GTI output power (a) day-1, (b) day-2, (c) day-3, (d) day-4, and (e) day-5

Figure 7 shows that the efficiency value tends to increase with increasing irradiation value, but as the irradiation value increases, the heat from the irradiation will make the temperature of the panel increase and cause the PV efficiency to decrease [13]. In general, the PV efficiency measured in this study is lower than the maximum expected theoretical value for the module (12-14%) [14]. After calculation with GUI, shows the same phenomenon, that is, PV efficiency tends to increase as irradiation increases. The largest percentage error with the actual data is 8.4%.

4. Effect of irradiation variation on GTI efficiency

In this study, a comparison of GTI efficiency from experimental results on a solar power simulator and GUI calculation results was carried out.



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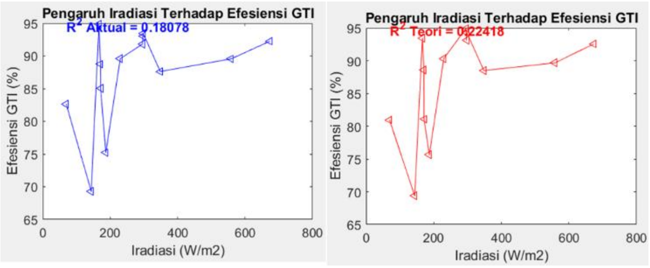

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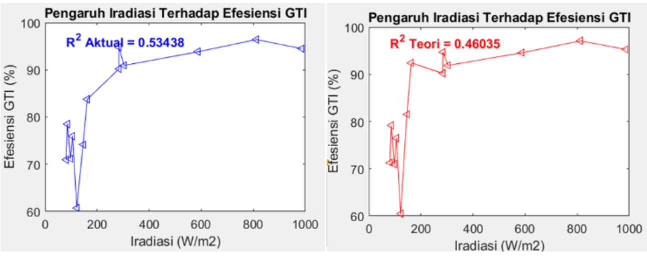

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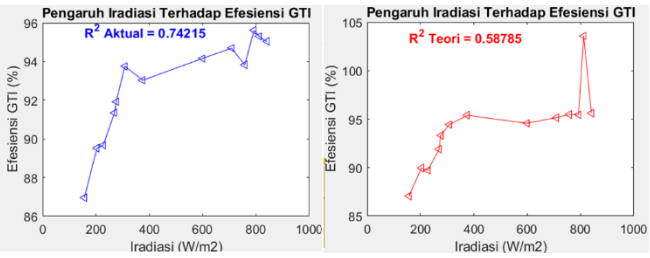

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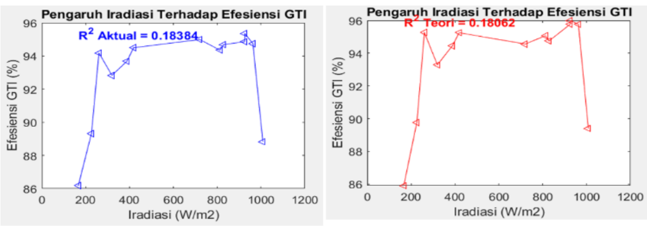


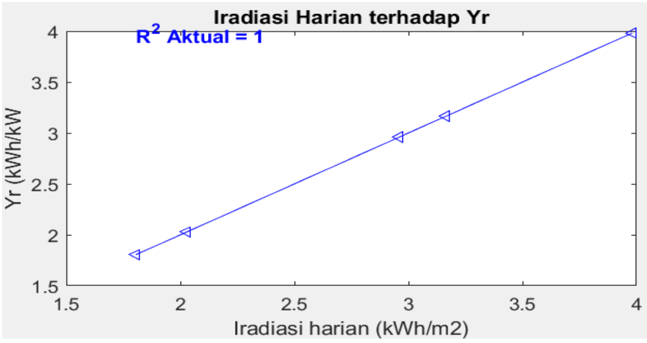
(e)

Figure 8 Effect of irradiation variation on GTI efficiency (a) day-1, (b) day-2, (c) day-3, (d) day-4, and (e) day-5

Based on Figure 8, when the irradiation value increases, the GTI efficiency value is higher and more consistent. After theoretical calculation with GUI, it shows the same phenomenon with the largest percentage error with actual data is 8%.

5. Effect of irradiation variation on solar power plant performance

This analysis uses irradiation data and GTI output power data. Then calculations were carried out using MATLAB GUI simulations to obtain the values of Yf, Yr, and PR.



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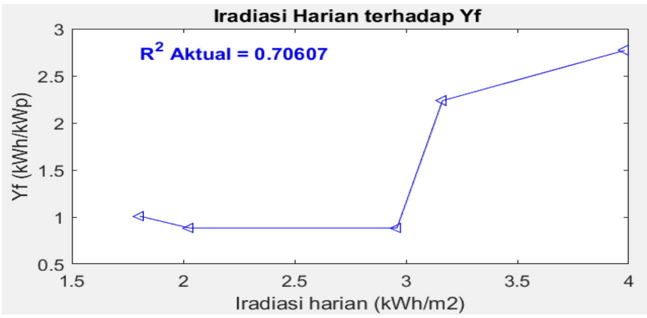

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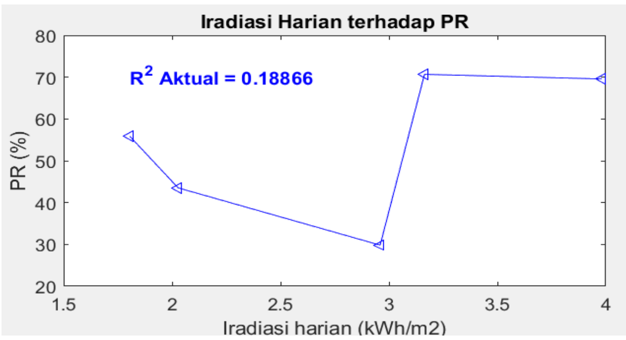

(c)

Figure 9 Effect of irradiation variation on solar power plant performance, (a) Yf, (b) Yr, and (c) PR.

Figure 9 shows that the Yf value also tends to increase. This happens because the higher the irradiation value, the higher the value of electrical energy production so that the Yf value is also high. On May 15, the Yf value was low due to environmental conditions (shadows) so that the solar power plant produced low electrical energy even though solar irradiation was high [15]. The Yr value states that the higher the daily irradiation value, the higher the Yr value. GSTC value is 1 kW/m2 so that the daily irradiation value and Yr are the same (directly proportional) and produce a linear graph. The PR also states that when the daily irradiation value increases, the PR value also tends to increase.

6. Effect of irradiation variation on export energy

This analysis uses irradiation data and energy export data. Then the effect of irradiation variation on the energy exported by the grid is analyzed.

Table 2 Effect of irradiation variation on export energy

Time	**Ir**radiation **(W/m²)**	**PLTS (W)**	Load**(W)**	**Impor (W)**	**Ekspor (W)**
		Day-1			
09.00	791,9	190	39,3	0	187,3
09.30	945,1	238	39,3	0	191,5
10.00	977,4	151	39,2	0	111,8
10.30	891,6	188	39,1	0	147,1
11.00	891,2	187	39,1	0	143,8
11.30	290,5	179	39	0	136,6
12.00	276,8	169	39,2	0	126,3
12.30	81	28,6	40,8	13,8	0
13.00	141,4	75,9	41,5	0	26,8
13.30	148,3	75,1	41,1	0	41,3
14.00	211,9	127	40,7	0	81,8
14.30	149,1	79,7	40,8	0	38
15.00	122,7	76,6	40,9	0	33,9
		Day-2			
09.00	171,1	150	41,4	0	116,3
09.30	295,2	213	41,2	0	192,2
10.00	558,7	472	41,3	0	401
10.30	348,3	177	41,4	0	140,7
11.00	297,2	226	41,5	0	200,2
11.30	69,5	28,1	41,1	17,3	0
12.00	673,3	155	41,4	0	115,8
12.30	298	185	41,4	0	137,8
13.00	229,8	129	41,3	0	86,2
13.30	187,1	85	40,8	0	44,2
14.00	171,5	87,6	40,8	0	44,1
14.30	166,7	73,5	40,9	0	32,6
15.00	143,8	35	41	4,7	0
		Day-3			
09.00	587,8	305	41	0	278
09.30	812,3	593	41,1	0	553,1
10.00	985,1	705	41	0	656,7
10.30	283,4	156	41	0	118,9
11.00	303,3	221	41	0	183,5
11.30	284	110	41,9	0	74,8
12.00	121,5	24,5	40,4	10,4	0
12.30	97,2	40	40,4	0	0
13.00	80,6	38,9	40,3	9,5	0
13.30	106,1	50,5	40,4	0	12,2
14.00	162,5	77,1	40,2	0	35,8
14.30	145,9	70	41	0	37,7
15.00	85,8	54,9	40,7	0	13,8
		Day-4			
09.00	758	501	40,8	0	444,1
09.30	598,6	451	40,8	0	426
10.00	841,1	593	40,7	0	546,1
10.30	227,7	139	39,9	0	98,3
11.00	308,4	210	39,8	0	159,4
11.30	203,6	128	39,8	0	85,9
12.00	269,6	190	39,8	0	165,5
12.30	792,7	609	40,4	0	394,5
13.00	375,5	267	40,1	0	144,8
13.30	275,8	0,178	39,6	0	122,9
14.00	812	567	39,8	0	527,2
14.30	708,6	535	39,8	0	500,1
15.00	156,4	100	39,4	0	36,4
		Day-5			
09.00	720,2	512	41,2	0	466,5
09.30	812,3	568	41	0	531,8
10.00	388,4	267	41,2	0	215,3
10.30	419,1	292	40,7	0	246
11.00	1008	644	41	0	603
11.30	828,6	659	40,9	0	607,9
12.00	925	646	40,8	0	599,5
12.30	962,7	649	40,8	0	598,8
13.00	226	142	40,8	0	107,7
13.30	319,7	220	40,6	0	174,9

14.00	925,4	657	41	0	608,1
14.30	166,5	106	40,3	0	61,3
15.00	260,6	178	40,6	0	134,8

Energy export in on-grid solar power plant occurs when the energy produced by the solar power plant can supply the load and there is unused energy or in other words, the energy produced exceeds the load requirements. The excess energy is exported to the grid. Conversely, if the solar power plant is unable to serve the load, then there is an import of energy from the grid.

Based on table 2, increasing irradiation affects the export power. The load used is 40 W. Increasing irradiation can increase the power of the solar power plant, so it can increase energy export to the grid.

B. Effect of Load Variation on Solar Power Plant Performance

Analysis of the effect of load variations on the performance of solar power plant aims to determine the effect of load variations on Pf. The Pf value can show the value of apparent power and reactive power which can cause wasteful use of electricity. After doing the calculation with the GUI, the following results were obtained:

Table 3 Effect of Load Variation on Solar Power Plant Performance

Load	**P Solar power (W)**	**LOAD**				**PLN**	
		P (W)	**Pf**	**S (VA)**	**Q (VAR)**	**Ekspor (W)**	**Impor (W)**
				R			
22,27	657	519	1	519	0	140,4	0
81,82	436	358	1	358	0	65,9	0
156,36	632	289	1	289	0	303,2	0
236,69	340	251	1	251	0	88,7	0
446,93	655	204	1	204	0	454,1	0
1956,83	355	117	1	117	0	254	0
RL (515,29 ohm, 1,63H)	444	144	0,63	228,6	177,54	316,2	0
RC (515,29 ohm,16 µF)	383	109	0,38	286,8	265,28	225,9	0
LC (1,63H, 16 µF)	313	38,9	0,37	105,1	97,64	280,8	0

Based on Table 3, the resistive load of 22.27Ω to 1956.83Ω shows that the real power (P) and apparent power (S) are the same and have a power factor (Pf) of 1, making it very efficient and not producing reactive power. In a combined RL load, the power factor (Pf) is 0.63, which occurs due to the presence of reactive c omponents. The reactive power generated is 177.51 VAR. In a combined RC load, the power factor is lower at 0.38, with reactive power at 265.33 VAR, indicating that the capacitive load draws a greater amount of reactive power. In the LC load, the power factor decreases further with reactive power at 97.67 VAR. The combination of LC results in a poor power factor because both loads draw reactive power. Reactive load can increase the demand for apparent power, leading to energy waste.

Export of power occurs when the energy produced by the solar power plant exceeds what is required by the load. In this case, the power is exported to the PLN grid. Based on table 1, the solar power plant is capable of supplying all types of loads without needing to draw power from the PLN grid.

IV. Conclusion

1. Irradiance plays a significant role in determining the overall performance of on-grid solar power systems. As the irradiation increases, the power generated by solar panels (PV) and grid-connected inverters (GTI) also rises, contributing to the improved efficiency of both. Performance parameters such as yield factor (Yf), reference yield (Yr), and performance ratio (PR) tend to increase with higher daily irradiation, indicating that the solar power system is more efficient and productive under conditions of higher irradiation. This is evidenced by the highest PV output of 746 W, GTI output of 705 W, PV efficiency of 10.27%, and GTI efficiency of 94.5%, which occurred under high irradiation of 985.1 W/m2. The PSIM simulation supports this finding by showing an increase in PV output as irradiation increases.
2. The variation in irradiation affects the value of Pf. Based on research, the worst Pf value is 0.37, which

is a combination of LC loads caused by high reactive power consumption. The best Pf is with resistive loads at 1, meaning that this load does not consume reactive power.

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