

Solar Irradiation Data Analysis Using Python and SPSS for Rooftop PV Design Based on Energy Import Export to Reduce Household Electricity Bills

Aprilia Sarah Kristina*, Rinaldy Dalimi

Universitas Indonesia, Indonesia

Email: apriliasarah@ui.ac.id*, rinaldy@eng.ui.ac.id

Keywords

Solar Irradiation;
NASA POWER;
Household Electricity
Consumption;
Python;
SPSS (Statistical Package for the
Social Sciences)

ABSTRACT

Solar energy is a promising renewable resource in Indonesia due to the country's high year-round solar availability. In rooftop photovoltaic systems, solar irradiation is a key factor affecting panel output, particularly on the DC side. This study addresses the limited integration of satellite-based irradiation analysis, technical data processing, statistical modeling, and household electricity consumption in a single framework for rooftop photovoltaic planning. The study aims to analyze the characteristics of solar irradiation in Depok City, estimate the DC output of a 400 Wp monocrystalline module, and simulate the contribution of rooftop photovoltaic systems to reducing grid-imported electricity and household electricity bills. A quantitative approach was applied using hourly NASA POWER data for January 2025 to January 2026 and actual residential electricity bill data from the same period. The irradiation dataset was cleaned and processed using Python, then analyzed in SPSS through descriptive statistics, assumption testing, correlation and simple linear regression. The results indicate that NASA POWER data can provide a reliable basis for estimating rooftop photovoltaic performance and that solar irradiation has a strong relationship with DC output. The simulation further shows that rooftop photovoltaic deployment can significantly reduce electricity imported from the PLN grid and lower household electricity costs under selected capacity scenarios. These findings support the use of integrated data driven methods for rooftop photovoltaic planning in urban residential settings.

INTRODUCTION

Electricity demand in Indonesia continues to increase along with population growth, urban expansion and the rising use of electrical equipment in daily life. This condition places pressure on the national electricity supply system and strengthens the urgency of expanding renewable energy utilization at both the utility and end user levels (Raihan, 2023; Kementerian ESDM, 2017). At the same time, Indonesia still faces major challenges in reducing dependence on fossil based electricity, even though the country has considerable renewable energy resources that can support a long term energy transition (Blazev, 2021; Burke et al., 2019; Lubis et al., 2025). In this context, solar energy is one of the most promising options because

of its broad availability throughout the year and its applicability across various sectors, including residential consumers.

For urban households, rooftop photovoltaic systems offer a practical approach to utilizing solar energy because electricity can be generated directly at the point of use without requiring additional land (Yayasan Mitra Hijau, 2021; Pongoh et al., 2023). Rooftop photovoltaic deployment is especially relevant for residential users who seek to reduce dependence on grid electricity and lower monthly electricity bills (Bayu & Windarta, 2021; Panjidinata, 2024). However, the performance of a rooftop photovoltaic system is not determined solely by installed capacity. It is strongly influenced by local solar irradiation conditions, technical specifications of the solar module, and the actual electricity consumption profile of the consumer (Diansyah et al., 2021; Effendi, 2023). Therefore, rooftop photovoltaic planning requires a structured and measurable analytical basis so that the proposed system is technically relevant to the characteristics of the site and the user's electricity demand.

Among the technical variables that influence photovoltaic performance, solar irradiation is one of the most important because it directly affects the DC output of the module (Yasin et al., 2023; Rahmanta et al., 2023). Higher irradiation generally increases the potential output power of a solar panel, whereas fluctuations in irradiation over time cause variations in energy production. For this reason, irradiation analysis is a crucial first step in rooftop photovoltaic studies, especially when the objective is to estimate energy production and match it with household electricity needs (Silalahi & Gunawan, 2022; Dwisari et al., 2023). In many residential cases, however, continuous local measurement data are not available. This limitation makes alternative meteorological data sources necessary for research and simulation purposes.

NASA POWER has become a relevant source of satellite based meteorological data for solar energy studies because it provides irradiation data for specific coordinates and time intervals that can be used to estimate solar energy potential (Wayan et al., 2022). Nevertheless, NASA POWER data are still raw data and cannot be used directly without preprocessing. Invalid values, missing entries, or abnormal observations may affect the quality of the analysis if they are not handled properly (Silalahi & Gunawan, 2022). In this study, Python was used to clean the hourly irradiation data, remove invalid values, organize the dataset, and calculate the estimated DC output of the solar module based on the technical parameters of the Powitt 400 Wp monocrystalline panel (Adnyani & Suartama, 2024). This stage is important because the validity of the simulation depends heavily on the quality of the processed input data.

After the technical dataset was prepared, the analysis was continued in SPSS to examine the relationship between solar irradiation and panel DC output using descriptive statistics, assumption testing, correlation, and simple linear regression (Sitopu & Purba, 2021). This statistical approach is important because rooftop photovoltaic planning should not rely only on technical assumptions, but should also be supported by quantitative evidence showing whether irradiation significantly explains the variation in output power. By combining Python based preprocessing and SPSS based statistical analysis, this study develops a framework that links environmental data with module performance in a more systematic way.

In addition to irradiation and technical module data, this study also uses actual electricity bill data from a residential house in Depok City for the period from January 2025 to January 2026 (Kementerian ESDM, 2023). The use of real household electricity bills makes the study

more applicable because the proposed rooftop photovoltaic system is evaluated not only in terms of potential generation, but also in terms of its contribution to reducing imported electricity from the PLN grid and lowering household electricity bills (Fikry & Triadi, 2024; Dzulkifli et al., 2024). Thus, the simulation is based on actual household demand rather than a generalized assumption of residential load.

Although many previous studies have discussed photovoltaic performance, solar potential estimation, or rooftop photovoltaic sizing, (Gunaldi et al., 2025; Effendi, 2023; Rahmanta et al., 2023) fewer studies integrate NASA POWER based irradiation analysis, Python based data preprocessing, SPSS based statistical testing and actual residential electricity bill data within a single framework. This gap is particularly important for household-scale applications in urban areas such as Depok, where practical rooftop photovoltaic planning requires both technical validity and direct relevance to consumer demand. Without such integration, it is difficult to evaluate the real contribution of rooftop photovoltaic systems to household electricity reduction under an energy import export scheme.

Based on this research gap, the present study aims to analyze the characteristics of solar irradiation in Depok City, estimate the DC output power of a monocrystalline solar module using processed irradiation data and simulate the contribution of rooftop photovoltaic deployment to reducing imported electricity and household electricity bills. The study is expected to provide a more structured analytical basis for rooftop photovoltaic planning based on real residential data and to contribute both academically and practically to the development of household solar energy utilization in urban areas.

METHOD

This study applied a quantitative research method with a statistical analysis and technical simulation approach (Sitopu & Purba, 2021). The research was conducted using a residential case study in Depok City, Indonesia, with the observation period covering January 2025 to January 2026. The study focused on the relationship between solar irradiation and the DC output of a monocrystalline solar module, and on the simulation of rooftop photovoltaic contribution to reducing imported electricity and household electricity bills.

The main data used in this study consisted of hourly solar irradiation data obtained from NASA POWER for the coordinates representing the study location in Depok City, actual monthly household electricity bill data for the same one-year period, and the technical specifications of the Powitt 400 Wp monocrystalline solar module (Wayan et al., 2022). The NASA POWER dataset was selected because continuous local field measurement data were not available, while the electricity bill data were used to represent the actual residential electricity demand profile. The technical module data were used as the basis for estimating DC output under varying irradiation conditions (Rahmanta et al., 2023).

The research procedure was conducted in several stages. First, the hourly irradiation data from NASA POWER were collected and preprocessed using Python. This stage included data cleaning, removal of invalid values such as abnormal entries, dataset arrangement, and preparation of valid hourly irradiation data for analysis (Adnyani & Suartama, 2024). After the dataset was cleaned, the DC output of the solar module was estimated using the technical parameters of the Powitt 400 Wp panel and the processed irradiation values.

Second, the processed data were analyzed statistically using SPSS. The analysis included descriptive statistics to summarize the characteristics of the variables, followed by assumption testing and simple linear regression to examine the relationship between solar irradiation as the independent variable and panel DC output as the dependent variable. The statistical procedures in the study included normality testing, linearity testing, regression analysis, residual normality testing, heteroscedasticity testing, Glejser testing and autocorrelation testing. These procedures were carried out to ensure that the regression model used in the study was statistically acceptable and suitable for interpretation.

Third, the statistical and technical results were used as the basis for rooftop photovoltaic simulation for the residential house. The simulation was developed by comparing estimated rooftop photovoltaic production with the actual household electricity demand profile derived from monthly electricity bills. Several capacity scenarios were evaluated to estimate energy production, the contribution of rooftop photovoltaic generation to household load, the remaining electricity imported from the PLN grid, and the potential change in household electricity bills under an energy import–export scheme.

Overall, the method was designed to integrate satellite-based irradiation data, Python-based preprocessing, SPSS based statistical analysis, and actual household electricity bill data into a single analytical framework. Through this approach, the study was able to assess rooftop photovoltaic performance not only from a technical perspective, but also from the practical perspective of household electricity consumption and grid import reduction.

RESULT AND DISCUSSION

The results and discussion of this study are presented in an integrated sequence that links data processing, statistical analysis, and rooftop photovoltaic simulation based on actual household electricity consumption. First, the study examines the cleaned solar irradiation dataset obtained from NASA POWER and its technical conversion into estimated DC output values of the Powitt 400 Wp module. Next, the discussion explains the statistical relationship between solar irradiation and panel output using SPSS, followed by the simulation of rooftop photovoltaic sizing and its contribution to reducing imported electricity from the PLN grid and household electricity bills. Through this structure, the findings are interpreted not only from a statistical perspective, but also from their practical relevance for residential rooftop photovoltaic planning in Depok City.

Processed Irradiation Data and Technical Conversion

The processed NASA POWER dataset for Depok City provided hourly solar irradiation data for the period January 2025 to January 2026 and was first cleaned in Python to remove invalid values before further analysis (Adnyani & Suartama, 2024; Wayan et al., 2022). This preprocessing stage was necessary because raw satellite-based data may contain anomalies or invalid entries that can affect the reliability of photovoltaic performance estimation if used directly. After cleaning, the irradiation data were converted into estimated DC output values for the Powitt 400 Wp monocrystalline module, producing a technical dataset ready for statistical analysis (Rahmanta et al., 2023).

To convert the cleaned irradiation data into technical photovoltaic output, this study used the equation $P_{DC} = P_{max} \times \frac{G}{1000}$, where P_{DC} represents the actual DC output power of the solar panel, P_{max} represents the rated maximum power of the module under Standard Test Conditions (STC), G represents the actual solar irradiation in W/m^2 , and $1000 W/m^2$ represents the reference irradiation level under STC. In this study, the value of P_{max} was set at 400 Wp according to the specification of the Powitt module, while the irradiation variable G was taken from the NASA POWER parameter ALLSKY_SFC_SW_DWN, which represents all-sky surface shortwave downward irradiance on a horizontal surface. Using this equation, each hourly irradiation value in the cleaned dataset was converted into a corresponding DC output value, generating a new technical dataset containing time, irradiation, and estimated panel output for further statistical analysis in SPSS.

Table 1. Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
ALLSKY_SFC_SW_DWN	8760	.00	909.62	187.4097	250.84380
P_DC_W	8760	0	364	74.96	100.338
Valid N (listwise)	8760				

The descriptive statistics in Table 1 summarize the hourly solar irradiation and the corresponding DC output of the Powitt 400 Wp module for the full one-year period of 8,760 hours. The ALLSKY_SFC_SW_DWN variable shows a minimum value close to 0 W/m^2 and a maximum of 909.62 W/m^2 , with an annual mean irradiation of 187.41 W/m^2 from $\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i$ and a relatively large standard deviation of 250.84 W/m^2 from $s_X^2 = \frac{\sum(X_i - \bar{X})^2}{8759} = 62922,612$, $s_X = \sqrt{62922,612} = 250,8438$, indicating substantial temporal variability in the available solar resource over the year. For the derived P_DC_W variable, the minimum value is 0 W and the maximum is 364 W, while the mean DC output is 74.96 W from $\bar{Y} = \frac{\sum Y_i}{8760} = 74,96$ W with a standard deviation of 100.338 W from $s_Y^2 = 10067,618$ and $s_Y = \sqrt{10067,618} = 100,338$ which reflects that the panel operates most of the time far below its 400 Wp rated power and only approaches this rating under high-irradiance conditions.

Together, these descriptive results confirm that the dataset covers a complete wide technical basis for analyzing the statistical relationship between solar irradiation and panel DC output.

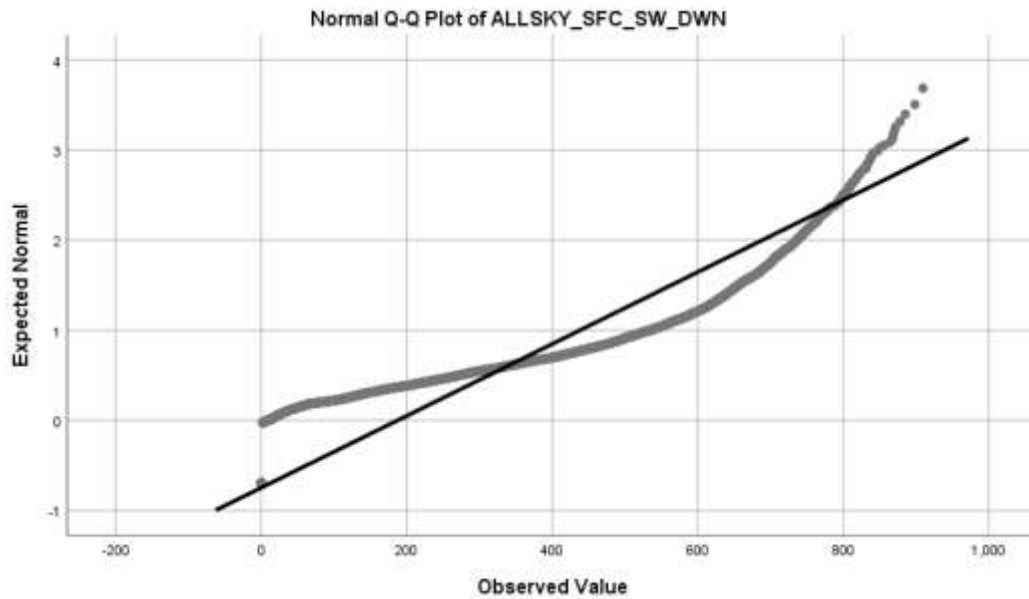


Figure 1. Normal Q-Q Plot

This normal Q–Q plot compares the distribution of the ALLSKY_SFC_SW_DWN irradiation data with a theoretical normal distribution. The points deviate from the straight reference line in both the lower and upper tails, especially at high irradiation values, indicating that the hourly irradiation data are not perfectly normally distributed and exhibit skewness and heavy tails, which is typical for solar resource time series.

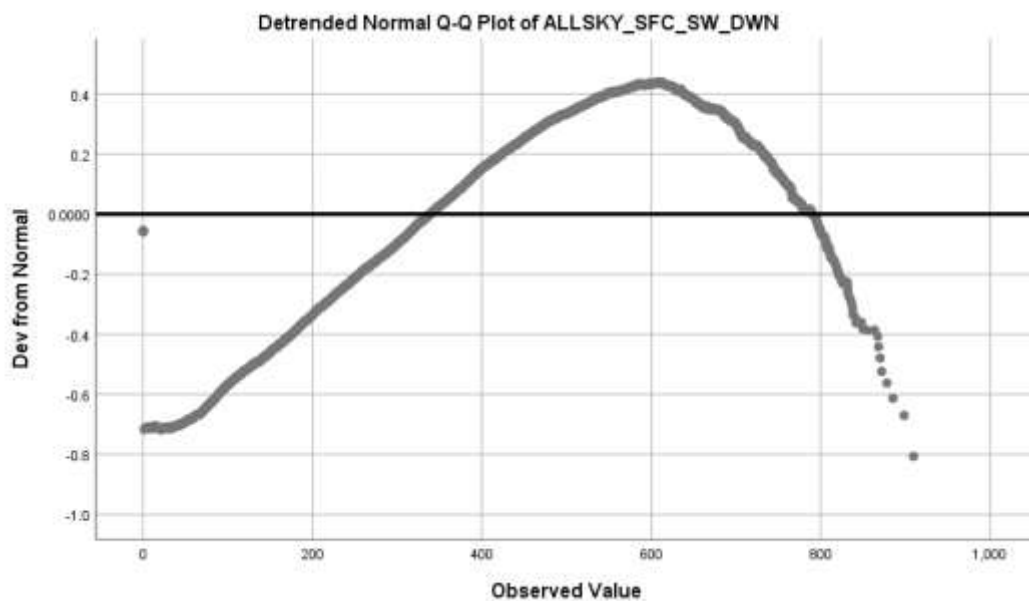


Figure 2. Detrended Normal Q-Q Plot

This detrended Q–Q plot shows the deviation of ALLSKY_SFC_SW_DWN from a theoretical normal distribution across the range of observed irradiation values. The systematic curved pattern, with negative deviations at very low and very high irradiation and positive deviations in the mid range, indicates that the irradiation data clearly depart from normality and exhibit a skewed, non Gaussian distribution, which is typical for hourly solar radiation time series.

Statistical Relationship between Irradiation and DC Output.

The statistical analysis showed a very strong positive linear relationship between solar irradiation and the estimated DC output of the photovoltaic module.

Table 2. Coefficients Linear Regression

Model	Unstandardized Coefficients		Standardized Coefficients	
	B	Std. Error	Beta	t Sig.
1 (Constant)	-9.521E-13	.000	.	.
ALLSKY_SFC_SW_DWN	.400	.000	1.000	.

a. Dependent Variable: P_DC_W

Based on the SPSS regression results, $\hat{Y} = a + bX$ the equation obtained $b = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sum(X_i - \bar{X})^2}$
 $a = \bar{Y} - b\bar{X}$ was $P_{DC,W} = -9.52 \times 10^{-13} + 0.400 \times ALLSKY_{SFC_{SW}_{DWN}}$ from $b = \frac{0,4\sum(X_i - \bar{X})^2}{\sum(X_i - \bar{X})^2} = 0,4$ and $a = \bar{Y} - b\bar{X} = 0,4\bar{X} - 0,4\bar{X} = 0$ Since the constant term is extremely small and practically equal to zero, the equation can be simplified to $P_{DC,W} \approx 0.400 \times ALLSKY_{SFC_{SW}_{DWN}}$ from $b = \frac{0,4\sum(X_i - \bar{X})^2}{\sum(X_i - \bar{X})^2} = 0,4$ This result indicates that every increase of 1 W/m² in solar irradiation increases the DC output of the panel by approximately 0.4 W. The regression coefficient is fully consistent with the technical conversion formula used in Python, where the Powitt module has a rated maximum power of 400 Wp under Standard Test Conditions, confirming that the relationship between irradiation and DC output is linear, positive, and physically meaningful. The final $\hat{P}_{DC,W} = -9,52 \times 10^{-13} + 0,400 \times ALLSKY_{SFC_{SW}_{DWN}} \approx 0,400 \times ALLSKY_{SFC_{SW}_{DWN}}$ and $R^2 = \frac{SSR}{SST} = 1, R = 1$

Distribution of Variables in the form of a Scatter Plot

The scatter plot of ALLSKY_SFC_SW_DWN versus P_DC_W shows that the data points form a very tight straight-line pattern rather than a random cloud. This indicates a perfectly positive linear relationship between solar irradiation and the DC output of the photovoltaic module, where higher irradiation is consistently followed by higher panel output in the same proportion. The visual pattern is fully consistent with the regression equation $P_{DC,W} \approx 0.400 \times ALLSKY_{SFC_{SW}_{DWN}}$, confirming that the derived DC output variable behaves as a deterministic function of the irradiation input.

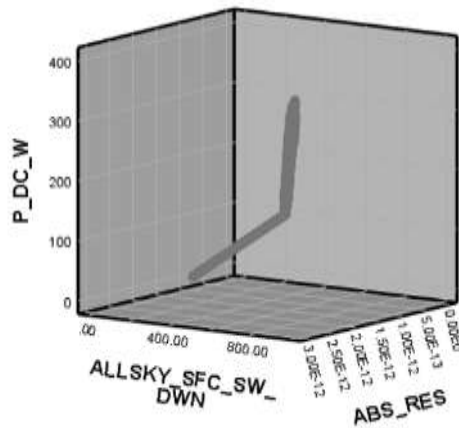


Figure 3. 3D Scatter Plot variable

The three dimensional scatter plot of ALLSKY_SFC_SW_DWN, P_DC_W, and ABS_RES shows that the data points lie along a single straight line in the irradiation–power plane, while the absolute residual values remain extremely close to zero for all observations. This pattern confirms that the DC output variable behaves as a deterministic linear function of solar irradiation with negligible modelling error, which is consistent with the regression equation $P_{DC_W} \approx 0.400 \times ALLSKY_SFC_SW_DWN$ and the way P_DC_W was computed from the irradiation data.

Results of Rooftop PV Simulation

The rooftop PV simulation was carried out using two design scenarios representing moderate and near full annual energy contribution to the household load, namely a 50% scenario and a 100% scenario. Based on the average monthly household electricity consumption of 756.5 kWh, the 50% scenario was designed to supply approximately half of the monthly demand, while the 100% scenario was designed to approach the full annual household electricity demand.

Table 3. Design parameters of rooftop PV system for 50% and 100% energy contribution scenarios

Scenario	Household consumption (kWh/month)	Target PV contribution (%)	Target PV energy (kWh/month)	Calculated capacity (kWp)	Selected capacity (kWp)	Number of 400 Wp modules
50%	756.5	50	378.25	3.152	3.2	8
100%	756.5	100	756.5	6.304	6.4	16

The required PV capacity was determined from the target monthly PV energy contribution and the assumed specific production of 120 kWh/kWp/month. The installed capacity was calculated using $P_{PV} = \frac{E_{PV}}{Y_{spec}}$, where P_{PV} is the required PV capacity (kWp), E_{PV} is the target monthly PV energy (kWh/month), and Y_{spec} is the monthly specific PV production (kWh/kWp/month). Using this approach, the 50% scenario required about 3.152

kWp and was rounded to 3.2 kWp, while the 100% scenario required about 6.304 kWp and was rounded to 6.4 kWp to match the use of 400 Wp modules.

The number of modules was calculated using $N = \frac{P_{PV}}{P_{mod}}$, where N is the number of PV modules and P_{mod} is the rated power of each module. With a module rating of 400 Wp, the 3.2 kWp system required 8 modules, whereas the 6.4 kWp system required 16 modules.

The energy output of the PV system was estimated using $E_{daily} = P_{STC} \times PSH \times \eta_{system}$, where E_{daily} is the daily PV energy output, P_{STC} is the installed PV capacity, PSH is the peak sun hours, and η_{system} is the system efficiency. Assuming 5 peak sun hours and 80% system efficiency, the 6.304 kWp configuration produced about 25.21 kWh/day, 756.3 kWh/month, and 9077.76 kWh/year, while the 3.152 kWp configuration produced about 12.608 kWh/day, 378.24 kWh/month, and 4538.88 kWh/year.

The contribution of rooftop PV to the household load was evaluated using $f_{PV} = \frac{E_{PV}}{\bar{E}_{month}} \times 100\%$, where f_{PV} is the PV contribution and \bar{E}_{month} is the average monthly household electricity consumption. After rounding to practical installed capacities, the 3.2 kWp system generated about 384 kWh/month or 4608 kWh/year, corresponding to about 50.76% of the annual household electricity demand, while the 6.4 kWp system generated about 768 kWh/month or 9216 kWh/year, corresponding to about 101.52% of the annual household electricity demand.

The installation area was estimated from the module area using $A_{total} = N \times A_{mod}$, where A_{mod} is the area of one module. Since each 400 Wp Powitt module has an area of about 1.98 m², the 8 module system required approximately 15.84 m², while the 16 module system required approximately 31.68 m².

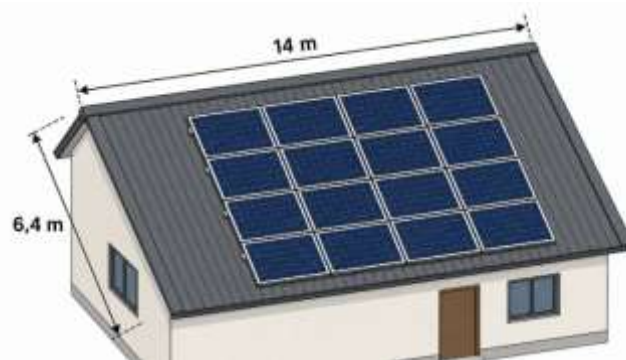


Figure 4. Using 16 module system required approximately 31.68 m²

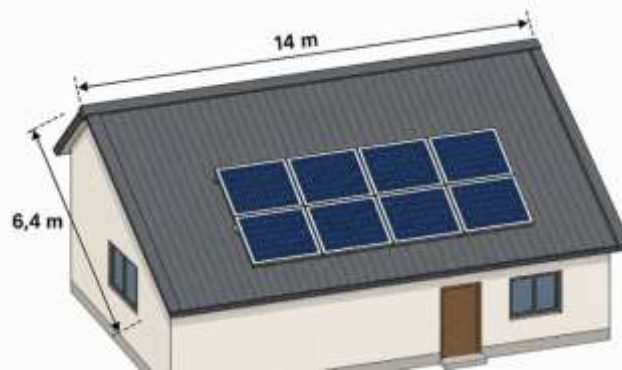


Figure 5. Using 8 module system required approximately 15.84 m²

These results indicate that the 3.2 kWp rooftop PV system is technically sufficient to provide about half of the annual household electricity demand with a relatively moderate roof area requirement. In contrast, the 6.4 kWp system is capable of approaching full annual energy coverage, although it requires a significantly larger installation area and does not necessarily eliminate monthly grid imports because the system operates under an on grid arrangement and PV generation is limited to daytime hours.

Monthly Grid Imports Eksports Energy under Rooftop PV Operation

In this subsection, the impact of rooftop PV operation on monthly grid electricity imports and the corresponding household electricity bills is evaluated for two penetration levels, namely 50% and 100% of the household load. The analysis compares the baseline condition (without PV) with both rooftop PV scenarios on a month by month basis, highlighting the reduction in energy imported from the grid and the resulting decrease in electricity expenditures. The presented graphs illustrate how increasing the share of on-site solar generation from 50% to 100% further lowers grid dependence and improves household energy cost performance.

Table 4. Monthly energy balance for 100% rooftop PV penetration in 2025

Month 2025	Household consumption (kWh)	PV production (kWh)	Difference (PV – load) (kWh)	Grid imports (kWh)	Exports to grid (kWh)
January	769	756.3	-12.7	12.7	0
February	640	756.3	116.3	0	116.3
March	536	756.3	220.3	0	220.3
April	761	756.3	-4.7	4.7	0
May	903	756.3	-146.7	146.7	0
June	720	756.3	36.3	0	36.3
July	781	756.3	-24.7	24.7	0
August	605	756.3	151.3	0	151.3
September	724	756.3	32.3	0	32.3
October	908	756.3	-151.7	151.7	0
November	894	756.3	-137.7	137.7	0
December	837	756.3	-80.7	80.7	0
Total	9,078	9,075.6	-2.4	558.9	556.2

The results in Table 4 show the monthly energy balance for the 100% rooftop PV penetration scenario in 2025. Overall, annual PV production (9,075.6 kWh) nearly matches the household electricity consumption (9,078 kWh), resulting in a very small net deficit of only 2.4 kWh over the year. During several months with relatively low demand, such as February, March, and August, PV generation exceeds the household load, leading to surplus energy that is exported to the grid. In contrast, months with higher consumption, including May, October, November, and December, still require additional electricity imports from the grid to fully meet the household demand. These patterns indicate that, even at 100% PV penetration on an annual basis, the household remains partially dependent on the grid in certain months while contributing excess energy in others.

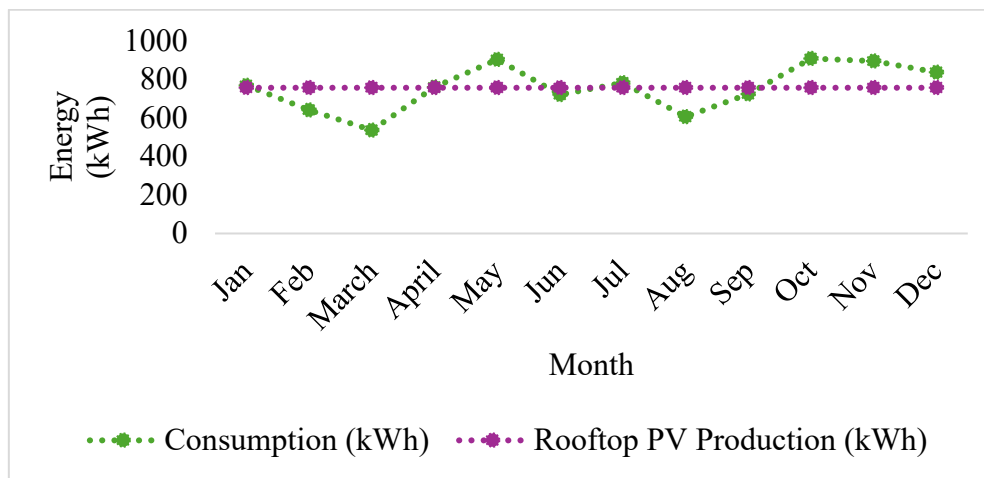


Figure 6. Monthly profile of household electricity consumption and rooftop PV production in 2025 for the 100% PV penetration scenario

The line graph in Figure 6 presents the monthly profile of household electricity consumption and rooftop PV production in 2025 for the 100% PV penetration scenario. Household demand shows noticeable seasonal variation, with higher consumption in May, October, November, and December, while lower values occur in March and August. In contrast, rooftop PV production remains almost constant at around 756 kWh per month, reflecting the sizing of the PV system based on annual energy matching rather than monthly load fluctuations. As a result, PV generation exceeds household consumption in some low demand months, where as additional grid electricity is still required in months with relatively higher consumption.

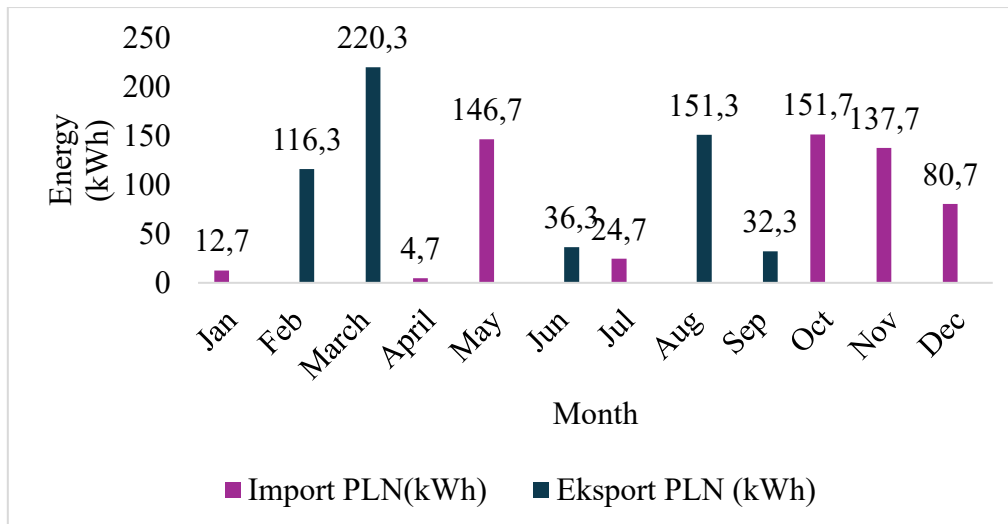


Figure 7. Monthly grid electricity imports and exports in 2025 for the 100% rooftop PV penetration scenario

The bar chart in Figure 7 illustrates the monthly grid electricity imports and exports in 2025 under the 100% rooftop PV penetration scenario. Grid exports occur mainly in months with relatively low household demand, such as February, March, June, August, and September, when PV generation exceeds the load. In contrast, substantial grid imports are observed in May, October, November, and December, indicating that the PV system alone is not sufficient to cover the higher household consumption in these months.

Table 5. Monthly energy balance for 50% rooftop PV penetration in 2025

Month 2025	Household consumption (kWh)	50% PV production (kWh)	Difference (PV – load) (kWh)	Grid imports (kWh)	Exports to grid (kWh)
January	769	378.2	-390.8	390.8	0
February	640	378.2	-261.8	261.8	0
March	536	378.2	-157.8	157.8	0
April	761	378.2	-382.8	382.8	0
May	903	378.2	-524.8	524.8	0
June	720	378.2	-341.8	341.8	0
July	781	378.2	-402.8	402.8	0
August	605	378.2	-226.8	226.8	0
September	724	378.2	-345.8	345.8	0
October	908	378.2	-529.8	529.8	0
November	894	378.2	-515.8	515.8	0
December	837	378.2	-458.8	458.8	0
Total	9,078	4,538.4	-4,539.6	4,539.6	0

The results in Table 5 present the monthly energy balance for the 50% rooftop PV penetration scenario in 2025. In this case, annual PV production reaches only 4,538.4 kWh, which is approximately half of the household electricity consumption of 9,078 kWh, leading to a sizable net deficit of 4,539.6 kWh that must be supplied by the grid. For all months, PV

generation remains below the household load, so no electricity is exported to the grid and the household relies entirely on grid imports to cover the remaining demand. When compared with the 100% PV penetration scenario, the 50% case results in substantially higher grid dependence and therefore a smaller potential reduction in electricity bills, even though both scenarios share the same temporal pattern of household consumption

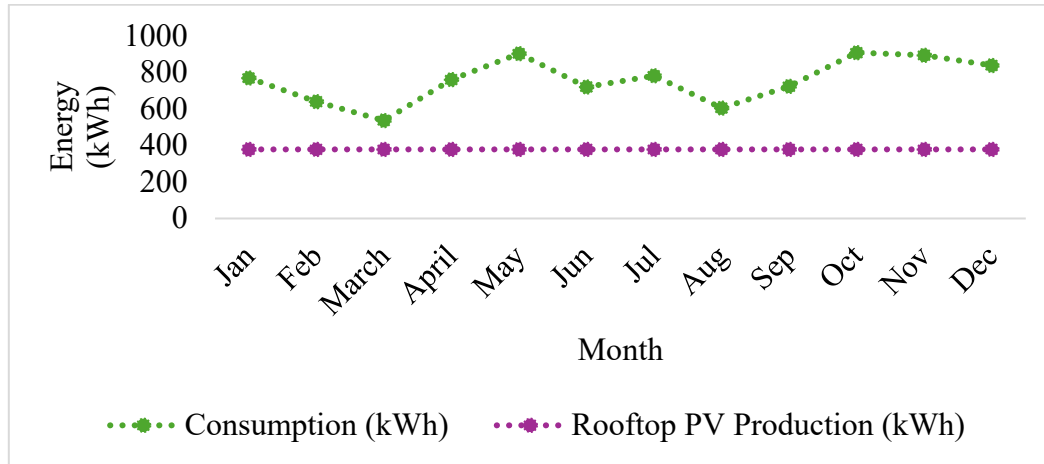


Figure 8. Monthly profile of household electricity consumption and rooftop PV production in 2025 for the 50% PV penetration scenario

The line graph in Figure 8 depicts the monthly profile of household electricity consumption and rooftop PV production in 2025 under the 50% PV penetration scenario. Household demand exhibits clear seasonal variations, with peak consumption occurring in May, October, and November and lower values in March and August. In contrast, the PV system generates an almost constant output of around 378 kWh per month, which is significantly lower than the household load in every month. Consequently, rooftop PV only covers a portion of the electricity demand, and the household must rely on grid imports throughout the year, with no surplus energy available for export.

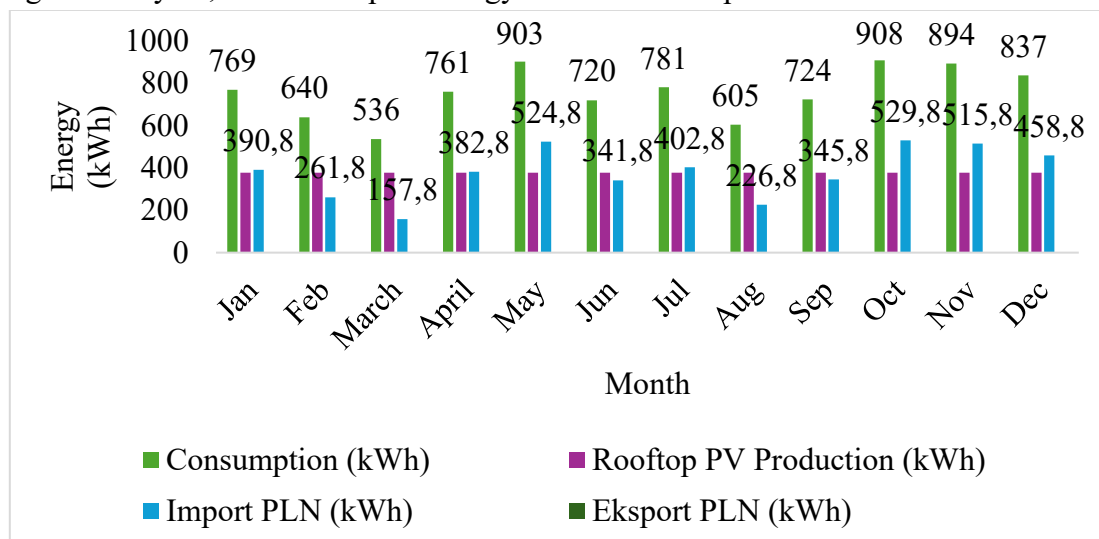


Figure 9. Monthly household electricity consumption, rooftop PV production, and grid imports in 2025 for the 50% PV penetration scenario

The bar chart in Figure X summarizes the monthly household electricity consumption, rooftop PV production, and resulting grid imports in 2025 under the 50% PV penetration scenario. In every month, PV generation remains substantially lower than the household load, so the remaining demand must be entirely supplied by the grid and no electricity is exported. Consequently, annual grid imports reach 4,539.6 kWh, which is equal to the net energy deficit between consumption and PV production, indicating that a 50% PV system can only partially offset household electricity use and provides a more limited reduction in grid dependence and electricity bills compared with the 100% PV penetration case.

Monthly Electricity Bill Reductions under 50% and 100% Rooftop PV Penetration

In this subsection, the effects of 50% and 100% rooftop PV penetration on monthly household electricity bills are evaluated. The analysis compares the original bills without PV to the bills under both PV scenarios, quantifying the financial savings achieved in each month. By examining the resulting bill reductions, the economic benefits of partially and fully offsetting household electricity consumption with rooftop PV can be clearly identified and compared.

Table 6. Monthly electricity bills and reductions for 50% and 100% rooftop PV penetration in 2025

Month 2025	Original bill (Rp)	50% PV bill (Rp)	100% PV bill (Rp)	50% reduction (Rp)	100% reduction (Rp)
January	1,307,251	663,834	21,582	643,417	1,285,669
February	1,087,699	445,728	0	641,971	1,087,699
March	910,899	268,252	0	642,647	910,899
April	1,293,504	650,087	7,988	643,417	1,285,516
May	1,534,005	891,746	249,252	642,259	1,284,753
June	1,223,662	580,373	0	643,289	1,223,662
July	1,326,049	684,121	41,940	641,928	1,284,109
August	1,028,294	385,353	0	642,941	1,028,294
September	1,231,360	587,965	0	643,395	1,231,360
October	1,543,612	899,338	257,254	644,274	1,286,358
November	1,519,039	876,086	234,895	642,953	1,284,144
December	1,421,847	779,804	137,202	642,043	1,284,645

The results in Table 6 summarize the monthly household electricity bills and corresponding reductions for the 50% and 100% rooftop PV penetration scenarios in 2025. For the 50% PV case, the monthly bills are consistently lower than the original bills without PV, with savings of around Rp 640,000 in most months. These savings arise because half of the annual electricity consumption is supplied by rooftop PV, thereby reducing the amount of energy purchased from the grid while the customer still pays for the remaining grid imports. In the 100% PV penetration scenario, the potential bill reductions are even more significant, often exceeding Rp 1,280,000 per month compared with the original bills. In several months, the electricity bill is reduced to zero or to a very small value, indicating that PV generation is sufficient to offset nearly all grid electricity charges under the applied tariff scheme. Overall,

the comparison between the two scenarios demonstrates that increasing rooftop PV penetration from 50% to 100% markedly enhances household electricity bill savings and strengthens the economic attractiveness of rooftop PV deployment.

CONCLUSION

This study demonstrates that rooftop photovoltaic (PV) systems designed using an energy import export approach can effectively reduce household dependence on grid electricity and lower monthly electricity bills. The simulation results confirm the research hypothesis that increasing rooftop PV penetration improves the household energy balance and provides greater economic benefits. In the 50% PV penetration scenario, the PV system is able to supply a substantial portion of the annual household demand, thereby reducing grid imports and producing consistent monthly bill savings. However, PV production remains below the household load in all months, which means that the household still depends on grid electricity throughout the year and no surplus energy is available for export.

In contrast, the 100% PV penetration scenario shows a much stronger technical and economic performance. Annual PV production is nearly equal to annual household electricity consumption, indicating that the system is capable of achieving an almost net-zero annual energy balance. Even though grid imports are still required during several high-demand months, surplus electricity is exported to the grid during low-demand months, demonstrating the operational effectiveness of the import–export scheme. This finding confirms that a properly sized rooftop PV system can significantly reduce grid reliance while maintaining supply adequacy over annual operation.

From the economic perspective, both PV penetration levels provide measurable reductions in monthly electricity bills, but the magnitude of savings differs substantially between the two scenarios. The 50% PV scenario results in moderate and relatively stable bill reductions because only part of the electricity demand is offset by PV generation. Meanwhile, the 100% PV scenario delivers much larger savings, with several months showing zero or nearly zero electricity charges. These results indicate that higher PV penetration not only improves technical energy performance but also strengthens the financial attractiveness of rooftop PV implementation for residential users.

In addition, the study also confirms that the issue of invalid or inconsistent values in the irradiation and energy-balance analysis could be successfully resolved. The invalid data were identified through validation and consistency checking, then corrected through recalculation and verification based on physically reasonable energy relationships. As a result, the final datasets used in the simulation became internally consistent and technically reliable. Therefore, the conclusions regarding household consumption, PV production, grid imports, grid exports, and electricity bill reductions are based on validated results and can be considered robust in supporting the overall findings of the study.

Overall, the study concludes that rooftop PV penetration has a direct positive impact on household energy performance and electricity cost reduction, with the 100% PV scenario providing the most optimal outcome among the evaluated cases. These findings support the use of rooftop PV as a practical strategy for reducing grid dependency and improving residential energy efficiency. They also indicate that the import export mechanism can enhance the utilization value of rooftop PV systems by allowing surplus electricity to contribute to the

overall annual household energy balance.

REFERENCE

- Adnyani, N. P., & Suartama, I. M. (2024). Exploring Python programming: A project-based learning approach in higher education. *Journal of Education Technology*, 8(2), 306–314. <https://doi.org/10.23887/jet.v8i2.68694>
- Amba, M. I., & Dalimi, R. (2023). Economic analysis of hybrid power plant (solar-diesel) on Kawaluso Island, North Sulawesi. *Jurnal EECCIS (Electrics, Electronics, Communications, Controls, Informatics, and Systems)*.
- Barus, D. H., & Dalimi, R. (2020). A review of Indonesia grid code adaptation toward variable renewable energy penetration. *AIP Conference Proceedings*, 2230(1), 050009.
- Barus, D. H., & Dalimi, R. (2021). Determining optimal operating reserves toward wind power penetration in Indonesia based on hybrid artificial intelligence. *IEEE Access*, 9, 165173–165183.
- Bayu, H., & Windarta, J. (2021). Tinjauan kebijakan dan regulasi pengembangan PLTS di Indonesia. *Jurnal Energi Baru dan Terbarukan*, 2(3), 123–132. <https://doi.org/10.14710/jebt.2021.10043>
- Blazev, A. S. (2021). *Global energy market trends*. River Publishers. <https://doi.org/10.1201/9781003152019>
- Burke, P. J., Widnyana, J., Anjum, Z., Aisbett, E., Resosudarmo, B. P., & Baldwin, K. G. H. (2019). Overcoming barriers to solar and wind energy adoption in two Asian giants: India and Indonesia. *Energy Policy*, 132, 1216–1228. <https://doi.org/10.1016/j.enpol.2019.05.055>
- Diansyah, I. F. N., Handoko, S., & Windarta, J. (2021). Implementasi dan evaluasi performa pembangkit listrik tenaga surya (PLTS) on grid: Studi kasus SMP N 3 Purwodadi. *Transient: Jurnal Ilmiah Teknik Elektro*, 10(4), 701–708. <https://doi.org/10.14710/transient.v10i4.701-708>
- Dwisari, V., Sudarti, S., & Yushardi, Y. (2023). Pemanfaatan energi matahari: Masa depan energi terbarukan. *OPTIKA: Jurnal Pendidikan Fisika*, 7(2), 376–384. <https://doi.org/10.37478/optika.v7i2.3322>
- Dzul kifli, R., Wahyuono, R. A., Suyanto, & Muntini, M. S. (2024). *Optimalisasi regulasi PLTS atap di Indonesia: Studi kasus terhadap kendala dan solusi*.
- Effendi, R. (2023). Analisis penggunaan energi surya fotovoltaik sebagai sumber energi alternatif. *Jurnal Teknik Industri Terintegrasi*, 6(4), 1298–1302. <https://doi.org/10.31004/jutin.v6i4.20634>
- Fikry, M. R., & Triadi, I. (2024). Evolusi regulasi energi baru terbarukan: Analisis perubahan orientasi aturan PLTS atap. *Birokrasi: Jurnal Ilmu Hukum dan Tata Negara*, 2(2), 364–373. <https://doi.org/10.55606/birokrasi.v2i2.1292>
- Gunaldi, G., Rahma, I. H. A., & Raharjo, S. E. (2025). Analisis potensi pembangkit listrik tenaga surya (PLTS) atap untuk mendorong net zero emission di kawasan pemukiman. Kementerian Energi dan Sumber Daya Mineral. (2017). *Rencana umum energi nasional (RUEN)*. Kementerian ESDM.
- Kementerian Energi dan Sumber Daya Mineral. (2023). *Statistik energi Indonesia 2023*. Ditjen EBTKE.

- Kurniyanto, F. W., & Setiawan, E. A. (2025). Utilization of advanced metering infrastructure (AMI) data for optimization of load management and dynamic pricing at PLN. *Journal Transnational Universal Studies*, 3(9), 219–238. <https://doi.org/10.58631/jtus.v3i9.178>
- López, G., Moreno, J. I., Amarís, H., & Salazar, F. (2014). Paving the road toward smart grids through large-scale advanced metering infrastructures. *Electric Power Systems Research*, 120, 194–205. <https://doi.org/10.1016/j.epsr.2014.05.006>
- Lubis, A. F., Saputra, M. R., & Khotami, R. S. (2025). *Hukum dan kebijakan energi terbarukan di Indonesia: Analisis strategi dan implementasi*. <https://doi.org/10.53866/jimi.v5i2.713>
- Oktaviansyah, Y., & Makkulau, A. (2023). Penerapan advance metering infrastructure (AMI) di PT PLN (Persero) dalam transformasi sektor energi Indonesia: Tantangan dan prospek masa depan.
- Panjidinata, N. A. (2024). Analisis dampak kebijakan pembangkit listrik tenaga surya atap PLN terhadap pengembangan energi terbarukan: Tantangan dalam harmonisasi regulasi investasi energi terbarukan. *Commerce Law*, 4(2), 488–506. <https://doi.org/10.29303/commercelaw.v4i2.5836>
- Paterakis, N. G., Erdinç, O., & Catalão, J. P. S. (2016). An overview of demand response: Key elements and international experience. *Renewable and Sustainable Energy Reviews*, 69, 871–891. <https://doi.org/10.1016/j.rser.2016.11.167>
- Pongoh, J., Langie, M., Tuwongkesong, S., Restiawan, W. P., & Tampemawa, J. (2023). PLTS sebagai energi alternatif di Indonesia yang ramah lingkungan. *Journal Central Publisher*, 1(4), 289–294. <https://doi.org/10.60145/jcp.v1i4.87>
- Purnomo, P., Habibi, M., & MK, I. G. (2026). Penilaian penerapan advanced metering infrastructure pada tahap awal dan keselarasannya dengan roadmap smart grid: Bukti empiris dari Indonesia. *Journal of Authentic Research*, 5(1), 116–131. <https://doi.org/10.36312/ny8yga92>
- Putra, I., & Manuaba, I. B. G. (2025). Literatur review tantangan dan teknologi dalam pengembangan advance metering infrastructure (AMI). *Majalah Ilmiah Teknologi Elektro*, 24(1), 1–8. <https://doi.org/10.24843/mite.205.v24i01.p01>
- Rahmanta, M. A., Syamsuddin, A., Tanbar, F., & Damanik, N. (2023). Analisis perkembangan teknologi modul photovoltaic (PV) untuk meningkatkan penetrasi pusat listrik tenaga surya (PLTS) di Indonesia. *Jurnal Offshore Oil Production Facilities and Renewable Energy*, 7(1), 22–33. <https://doi.org/10.30588/jo.v7i1.1509>
- Raihan, A. (2023). An overview of the energy segment of Indonesia: Present situation, prospects, and forthcoming advancements in renewable energy technology. *Journal of Technology Innovations and Energy*, 2(3), 37–63. <https://doi.org/10.56556/jtie.v2i3.599>
- Silalahi, D., & Gunawan, D. (2022). *Solar energy potentials and opportunity of floating solar PV in Indonesia*. Penerbit BRIN. <https://doi.org/10.55981/brin.562.c5>
- Sitopu, J. W., & Purba, I. R. (2021). Pelatihan pengolahan data statistik dengan menggunakan aplikasi SPSS. *Development and Sustainable Technology*, 3(2), 45–52.
- Wayan, I. W., Arnawa, I. W., & Utami, N. P. S. (2022). NASA Power's: An alternative rainfall data resources for hydrology research and planning activities in Bali Island, Indonesia. *Jurnal Inovasi Penelitian dan Edukasi*, 3(1), 45–54.

- Yasin, M., Apriaskar, E., & Djuniadi, D. (2023). Simulasi monitoring arus, tegangan dan daya panel surya. *Emitor: Jurnal Teknik Elektro*, 22(2), 87–92. <https://doi.org/10.23917/emitor.v22i2.21092>
- Ye, Y., Qian, Y., Sharif, H., & Tipper, D. (2012). A survey on smart grid communication infrastructures: Motivations, requirements and challenges. *IEEE Communications Surveys & Tutorials*, 15(1), 5–20. <https://doi.org/10.1109/SURV.2012.021312.00034>
- Yayasan Mitra Hijau. (2021). *Pembangunan, operasional dan pemeliharaan PLTS atap: Buku panduan*. Yayasan Mitra Hijau.