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Optimisation of home grid-connected photovoltaic systems: performance analysis and energy implications

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Abstract
In the increasing need for renewable energy, grid-connected photovoltaic (GCPV) systems at home are a promising solution to reduce dependence on fossil fuels. This article examines the optimization of home GCPV systems, focusing on performance analysis and the resulting energy implications. It also analyzes the performance of a photovoltaic system with a capacity of 3000 Wp connected to the electricity network to people's homes. Through case studies using empirical data and computer simulations, this research evaluates various GCPV system configurations to determine the most energy-efficient scenario. Without the influence of shadows, this system is designed to meet daily household energy needs with seasonal modulation. The simulation results show annual energy production of 4446 kWh and energy use of 3379 kWh, with a performance ratio of 83.79% and a diesel fraction of 55.40%. This article discusses the simulation methodology, results, and implications of using PV systems in the context of energy efficiency and sustainability.

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1. Introduction
In the modern era, using renewable energy has become a global priority to overcome the problem of dependence on fossil fuels and the environmental impacts it causes. With its strategic location on the equator, Indonesia has great potential to develop solar energy. However, integrating solar energy technology into the domestic energy network still faces various challenges, ranging from system efficiency to economic feasibility (Abdalla et al. 2023; Toghyani and Saadat 2024; Ukoba et al. 2024). Optimisation of grid-connected photovoltaic

systems can be a promising solution in increasing energy use efficiency while utilizing sustainable energy sources (Ebi et al. 2022; Alharbi et al. 2023; Borkowski et al. 2023; Zhang et al. 2023; Díaz-Bello et al. 2024). The availability of renewable energy sources in Indonesia is currently sufficient to reduce dependence on fossil energy. Several previous publications have reported abundant renewable energy sources in Indonesia (Erdiwansyah et al. 2019b, a, 2021, 2022). However, Indonesia's current use of energy sources has yet to be carried out optimally.

Using renewable energy is essential in Indonesia, especially in reducing dependence on fossil energy and carbon emissions (Habiba et al. 2023; Siddique et al. 2023; Rahman et al. 2024). Photovoltaic (PV) systems offer a promising solution, especially in areas with high solar insulation, such as in one of the residential areas of Meunasah Baktrieng Village, Kuta Baro District, Aceh Besar Regency, Aceh Province, Indonesia. This study focuses on a PV system connected to a grid in residential areas using the AEG AS-M606-300 PV module without any shadow effects (Monjo et al. 2024; Nafeh et al. 2024; Salau and Alitasb 2024). Residential housing in Meunasah Baktrieng Village, Kuta Baro District, Aceh Besar Regency, Aceh Province, Indonesia, is an example of the application of a network-connected photovoltaic system designed to meet the daily energy needs of households. With a total capacity of 3000 Wp and without any obstructing shadow influences, this system optimises solar energy reception. Studying these systems provides insight into how system design and orientation can influence energy output, which is essential for designing more efficient and economical systems in the future.

Analysing the performance of these grid-integrated photovoltaic systems is essential to identifying areas where this technology can be improved to maximise the use of renewable energy on a household scale (Li et al. 2022; Shah et al. 2023; Alsibiani 2024; Maka and Chaudhary 2024). For example, understanding variables such as performance ratio and solar fraction provides an essential picture of the system's effectiveness in converting solar energy into electricity, and the proportion of energy needs met through renewable energy. Optimisation strategies can be developed here to improve overall system performance (Izci et al. 2023; Jin et al. 2023; Li et al. 2024; Lu et al. 2024). The implications of implementing this photovoltaic system for national and regional energy policies are also essential and must be considered (Laevens et al. 2021; Che et al. 2022; Lucchi 2022). A deeper understanding of the results and success of implementing these systems can assist policymakers and practitioners in formulating more effective policies and directing investments towards the most profitable and sustainable technologies. Therefore, performance analysis and optimisation of photovoltaic systems connected to residential networks contribute to energy efficiency and long-term sustainability goals.

The main objective of this article is to analyse and optimise the performance of grid-connected photovoltaic systems in residential areas. This study aims to assess the existing system's energy use efficiency and performance ratio and identify potential improvements through technical and operational modifications. Through this analysis, the article seeks to provide data-based recommendations on ways to increase energy production capacity and the effectiveness of photovoltaic systems in meeting household energy needs sustainably. Thus, this study aims to provide insights to assist decision-making regarding implementing and scaling photovoltaic technology in other tropical regions with similar conditions.
This article brings the latest in photovoltaic system performance analysis by focusing on using state-of-the-art models and simulations calibrated with actual local climate and energy consumption data. Another novelty is the integrated approach in assessing seasonal effects on

energy consumption and production, often overlooked in similar studies in tropical regions. This article also integrates performance ratio analysis with solar fraction evaluation to effectively measure how much energy demand can be met through a photovoltaic system under various conditions. This provides insight into the potential of integrating grid-connected photovoltaic systems to reduce dependence on fossil energy and support sustainable energy policies. Additionally, by using the latest data and simulation technologies, such as PVsyst, this study offers a more accurate and relevant evaluation of the performance of photovoltaic technologies in the current geographic and technological context.

2. Material and Methodology

Data was collected using PVsyst V7.2.5 software, which simulates energy output based on geographic parameters, module orientation and household energy needs. No shading scenarios are defined in the simulation, indicating optimisation of sunlight reception. Household energy needs are mapped based on seasonal consumption, assuming an average daily energy use of 9.3 kWh. The PV design system designed in this research is shown in **Fig. 1**.

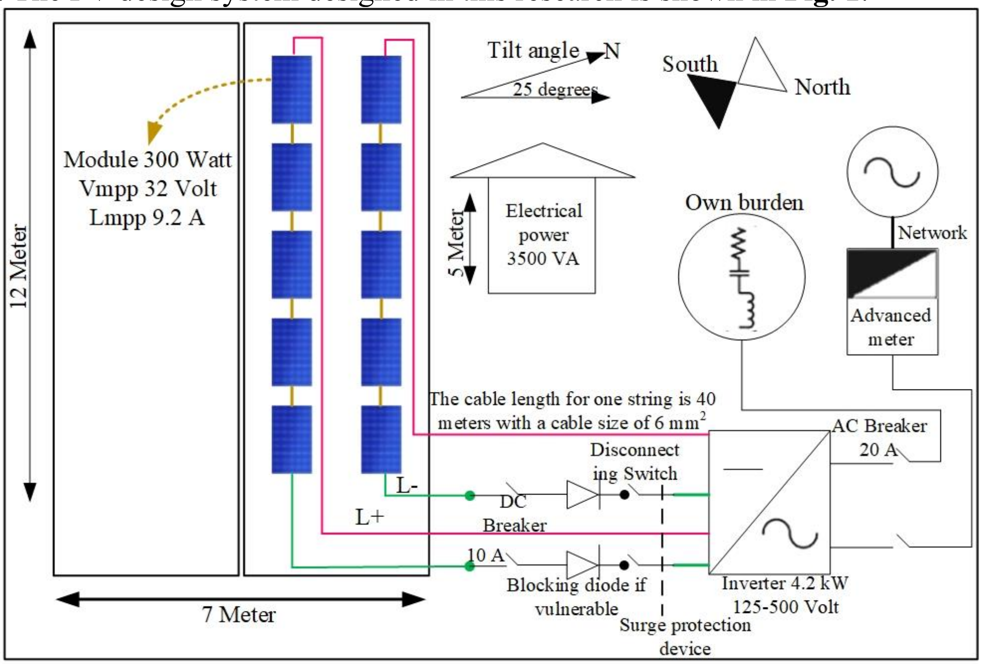

Fig. 1. Rooftop solar power plant design

Fig.2 is a schematic interpretation of a photovoltaic system circuit optimised for residential use. Strings of diodes connected in parallel indicate a vital component in managing the flow of electrical current generated by solar panels, ensuring that the current flows consistently and safely to the inverter. The inverter, represented by a box with plus and minus symbols, is a crucial device that converts direct current (DC) produced by solar panels into alternating current (AC) that household appliances can use to be fed to the grid. Resistors depicted with wavy lines indicate the electrical load of the home or grid network to which the photovoltaic system is connected. Optimisation of these circuits may involve increasing diode efficiency, selection of inverters with minimal power losses, and load management to maximise the use of generated energy, all of which are important in analysing system performance and its energy implications on home electricity use.

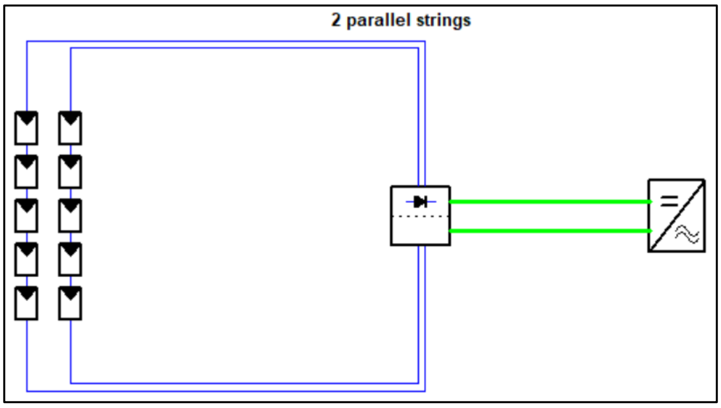

Fig. 2. Diode rectifier circuit schematic for grid-connected photovoltaic systems

2.1 Material

The primary tool used to analyse the performance of photovoltaic systems connected to residential networks is PVsyst V7.2.5 software. PVsyst is a highly acclaimed simulation tool for photovoltaic systems, which allows users to design photovoltaic systems and model the expected energy output based on various parameters. This tool facilitates detailed modelling of panel orientation, inverter characteristics, geographic effects, and meteorological data.

2.2 Methodology

This research methodology includes several main steps:

a. Data collection
   - **Geographical and Meteorological Data:** Location of housing for residents of Meunasah Baktrieng Village, Kuta Baro District, Aceh Besar Regency, Aceh Province, Indonesia, with climate data obtained from Meteonorm 8.0 which covers the data period from 2007 to 2023.
   - **Energy Consumption Data**: Daily household energy needs are analysed based on daily equipment use during the four seasons of one year.

b. Photovoltaic System Simulation
   - **System Configuration**: We are using PVsyst to set up a photovoltaic system with 10 AEG PV modules, model AS-M606-300, with a total capacity of 3000 Wp, and an AEG model AS-IR01-4000 inverter.
   - **Array Orientation and Tilt**: The photovoltaic modules are positioned on a fixed plane with a tilt of 25 degrees and an azimuth of -15 degrees.
   - **Load Analysis**: This annual performance simulation is based on household energy consumption adjusted for the season without the influence of shading.

c. Output Analysis
   - **Analysis of Energy Produced and Used**: Evaluation of the energy produced by the PV system and the energy used by the household.
   - **Calculation of Performance Ratio (PR) and Solar Fraction (SF):** Assess the system's efficiency in converting radiation into electrical energy and how much household energy consumption can be met by the PV system.

d. Evaluation and Optimization
   - **System Loss Analysis**: This analysis accounts for energy losses through system components such as soiling, mismatch, and thermal losses.
   - **Improvement Suggestions**: Based on simulation results, identify potential areas for improving efficiency, such as improving load management or modifying system configuration.

Using this combination of tools and methods, this research aims to provide in-depth insight into grid-connected photovoltaic systems' performance and optimization potential in the household context.

3. Result & Discussion

Data obtained by simulating a photovoltaic system in one of the residential areas using PVsyst V7.2.5 show system performance and effectiveness in specific geographic and climatic conditions in residential areas of Meunasah Baktrieng Village, Kuta Baro District, Aceh Besar Regency, Aceh Province, Indonesia. **Table 1** depicts the total energy use for various devices in the home during the summer, from June to August, and the fall, from September to November. During the summer, ten LED or fluorescent lamps with a consumption of 10W per lamp were recorded for 5 hours each day, resulting in a total consumption of 500Wh. One TV/PC/Mobile uses 80W and is operated for 7 hours, consuming 560Wh. For household appliances such as ovens and blenders, three units with 100W usage each operate for 7 hours, contributing 2100Wh. One refrigerator or freezer is operated 24 hours a day with a consumption of 1800Wh. One dish or clothes washer uses 750Wh in 3 hours. Stand-by consumption, which lasts 24 hours, accounts for 144Wh. Total daily energy consumption during summer is 5854Wh.

For fall, lamp usage remains the same, but there is an increase in TV/PC/Mobile usage, with two units using 100W for 5 hours, reaching 1000Wh. Only one household appliance consumed 500W for 5 hours, producing 2500Wh. Both refrigerators or freezers operate 24 hours with a total of 1598Wh. The dish or clothes washer operates for 2 hours and uses 2000Wh. There is additional ventilation with one unit operating 24 hours at 100W total, adding 2400Wh. Stand-by consumption remains the same, 144Wh. The total daily energy consumption during autumn is 7142Wh. This data shows an increase in energy use from summer to autumn, which may be due to the use of additional equipment such as ventilation and an increase in the number and use of TV/PC/Mobile. The daily energy total for fall reached "10142Wh/day," indicating higher usage during those months. This analysis provides an overview of changes in household energy needs as the seasons change.

Table 1. Total energy use June-November

Parameter	Summer (Jun-Aug)				Autumn (Sep-Nov)			
	Number	Power	Use	Energy	Number	Power	Use	Energy
Lamps (LED or fluo)	10	10W/lamp	5.0	500	10	10W/lamp	5.0	500
TV / PC / Mobile	1	80W/app	7.0	560	2	100W/lamp	5.0	1000
Domestic appliances	3	100W/app	7.0	2100	1	500W/app	5.0	2500
Fridge / Deep-freeze	1	-	24	1800	2	-	24	1598
Dish- & Cloth-washers	1	-	3	750	1	-	2	2000
Ventilation	-	-	-	-	1	100W tot	24.0	2400
Stand-by consumers			24.0	144			24.0	144
Total daily energy				5854Wh/day				10142Wh/day

Table 2 displays energy use from December to May, divided into winter (December-February) and spring (March-May). In winter, LED or fluorescent lights are used 6 hours a day, using 800Wh. A TV, PC or mobile device consumes 1200Wh, assuming 6 hours of use a day. Household appliances use 3000Wh, assuming 6 hours of use a day. A refrigerator or freezer uses 1598Wh for 24 hours a day. The dish and clothes washer use 2000Wh in 2 hours. Ventilation consumes 2400Wh for 24 hours a day, and stand-by consumption remains at 144Wh, resulting in a total daily energy use of 10942Wh. In spring, lamp usage reduces to 5

hours daily, producing 500Wh. Use of other devices remains the same except for household appliances, which are reduced to 5 hours a day with a consumption of 2500Wh, giving a total daily energy use of 10142Wh.

Compared to **Table 1**, which covers June to November, there are changes in energy use and consumption across categories. In summer (June-August), total energy use in **Table 1** is 5854Wh per day, while in **Table 2**, for winter (December-February), total energy use almost doubles to 10942Wh per day. The leading cause of this increase is 24-hour ventilation in winter and the increased use of lights, TV/PC/Mobile, and household appliances. Autumn (September-November) from Table 1 and winter in **Table 2** show no housing (10142Wh per day). Overall, there is a significant increase in energy use from summer and fall to winter, possibly due to more extended lighting requirements and more intensive use of appliances to heat the home. The decline into spring shows a reduction in light use, reflecting longer days and perhaps reduced heating needs. This analysis underscores the importance of considering seasonality in managing household energy consumption.

Table 2. Total energy use December-May

Parameter	Winter (Dec-Feb)				Spring (Mar-May)			
	Number	**Power**	**Use**	**Energy**	**Number**	**Power**	**Use**	**Energy**
Lamps (LED or fluo)	10	10W/lamp	6.0	800	10	10W/lamp	5.0	500
TV / PC / Mobile	2	100W/app	6.0	1200	2	100W/lamp	5.0	1000
Domestic appliances	1	500W/app	6.0	3000	1	500W/app	5.0	2500
Fridge / Deep-freeze	2	-	24	1598	2	-	24	1598
Dish- & Cloth-washers	1	-	2	2000	1	-	2	2000
Ventilation	1	100W/app	24.0	2400	1	100W tot	24.0	2400
Stand-by consumers			24.0	144			24.0	144
Total daily energy				10942Wh/day				10142Wh/day

The installed photovoltaic system with a capacity of 3000 Wp produced 4446 kWh of energy annually, while household energy consumption was recorded at 3379 kWh per year. Meanwhile, the total energy production (inverter input) is 4.06 kWh/kWp/day, as shown in **Fig. 3(a)**. This shows that the system can produce more energy than it consumes, which indicates the potential for surplus power that can be utilised further, either for storage or reinjected into the grid. The system recorded a performance ratio (PR) of 83.79%, which indicates a high energy conversion rate and sound system operational efficiency, as presented in **Fig. 3(b)**. The solar fraction (SF) reached 55.40%, indicating that more than half of household annual energy needs can be met directly from this photovoltaic system. This is economically and ecologically relevant, reducing dependence on non-renewable energy sources.

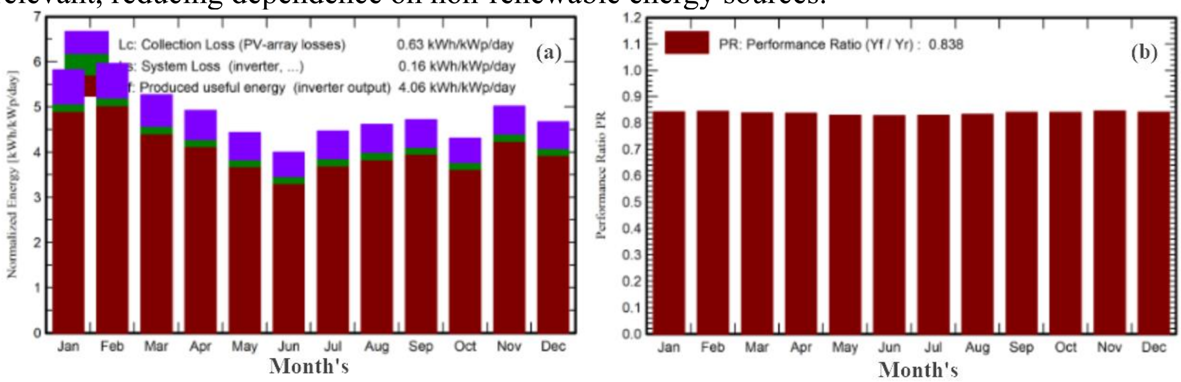

Fig. 3. (a) Normalized productions (per installed kWp), (b) Performance Ratio

The data also shows fluctuations in energy consumption between seasons, with winter recording higher energy use than other seasons. This is important to consider when planning system capacity to meet peak demand and adjusting energy storage or load management strategies. Analysis of energy losses shows that the main losses come from temperature factors (-8.09%), module incompatibility (-2.10%), and losses by cables and wiring (-0.58%), as presented in **Fig. 4**. Although these losses are considered normal in photovoltaic systems, there is potential to reduce these losses through better component selection or optimised system design.

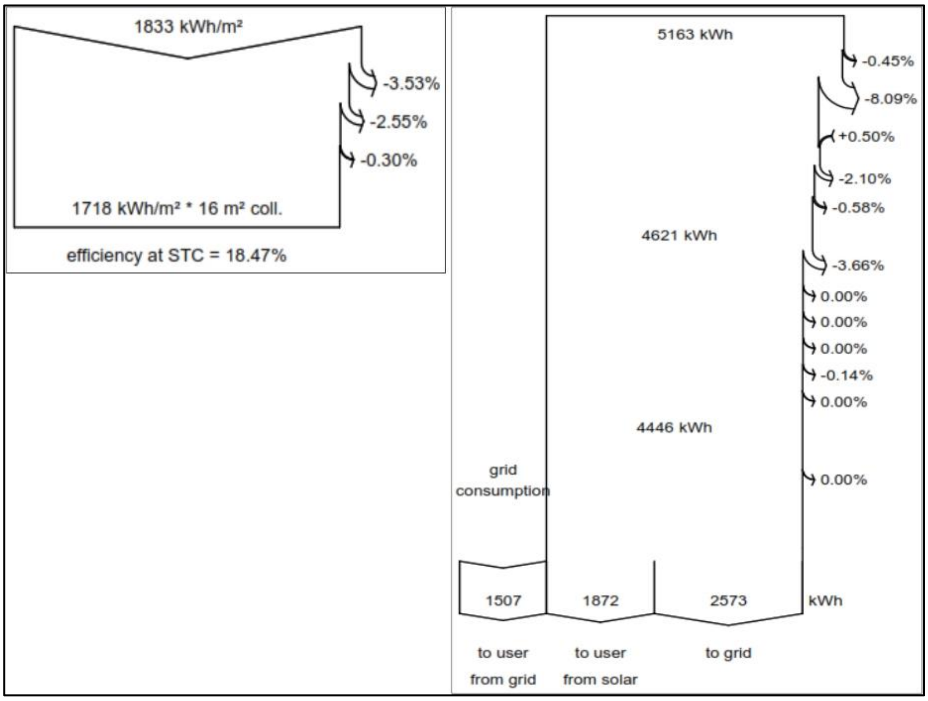

Fig. 4. Energy loss analysis

Table 3 shows monthly performance data of photovoltaic systems connected to the home network, including horizontal global irradiation (GlobHor), horizontal diffuse irradiation (DiffHor), ambient temperature (T_Amb), global irradiation that occurs in the collector field (GlobInc), effective irradiation that corrected for angle of incidence and dimming (GlobEff), adequate energy of the array (EArray), energy used by the user (E_User), energy from solar (E_Solar), energy injected into the grid (E_Grid), and energy received from the grid (EFrGrid). From these data, several significant findings can be identified. First, the monthly variability of irradiation reflects seasonal influences on photovoltaic system performance. This can be seen from global irradiation, which tends to be higher during summer (June to August) and lower in winter (November to January). Second, there is a correlation between the irradiation occurring in the collector field and the adequate energy produced by the array, indicating the system's conversion efficiency.

The energy the user uses (E_User) appears consistent throughout the year, indicating stable energy demand from home. In contrast, the energy from solar (E_Solar) and the energy injected into the grid (E_Grid) show more significant variations, highlighting the interaction between energy production photovoltaics and home consumption. The energy received from the grid (EFrGrid) also reflects the home's dependence on the grid, especially during months with lower irradiation. Overall, this data provides an overview of how photovoltaic systems can be optimised to increase energy independence and reduce dependence on the grid while highlighting existing challenges, such as efficiency being affected by seasonal conditions. This analysis helps understand the performance of photovoltaic systems in real scenarios and its implications for grid-connected home energy strategies.

Table 3. Balances and main results

Categories	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	159.0	66.75	26.88	180.5	176.8	471.9	339.2	206.3	249.9	132.9
February	156.4	77.83	27.31	167.0	163.5	437.6	306.4	197.5	225.5	108.9
March	165.8	80.25	27.52	163.4	159.4	426.1	314.4	191.1	219.4	123.3
April	163.4	78.05	27.54	147.9	143.4	385.9	304.3	185.3	186.2	119.0
May	163.6	78.95	28.29	137.5	143.4	356.9	314.4	186.3	156.1	128.1
June	146.2	76.48	28.12	119.9	115.1	312.0	175.6	57.4	240.6	118.2
July	168.1	80.92	28.47	138.5	133.0	359.6	181.5	59.0	285.5	122.4
August	163.1	80.65	28.14	143.0	138.1	372.2	181.5	60.2	297.1	121.3
September	148.7	82.52	27.28	141.6	137.6	370.6	304.3	186.3	170.5	118.0
October	132.1	80.04	27.17	133.7	130.3	351.4	314.4	176.0	161.3	138.4
November	138.0	71.59	26.49	150.7	147.2	396.6	304.3	178.4	204.1	125.9
December	129.0	67.13	26.76	145.0	141.8	380.2	339.2	188.6	177.3	150.6
Year	1833.3	921.16	27.50	1768.6	1718.4	4621.1	3379.4	1872.4	2573.5	1507.1

Legends

GlobHor	Global horizontal irradiation	EArray	Adequate energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_User	The energy supplied to the use
T_Amb	Ambient Temperature	E_Solar	Energy from the sun
GlobInc	The global incident in coll. plane	E_Grid	Energy injected into the grid
GlobEff	Effective Global, corr. for IAM and shadings	EFrGrid	Energy from the grid

Fig. 5 shows the relationship between 'Global incidents in coll. Plane [kWh/m²/day]' on the horizontal axis and 'Available Solar Energy [MWh/year]' on the vertical axis. The data is provided for one year, from January 1 to December 31. This graph shows a positive linear correlation between global irradiation falling on the collector field and the yearly amount of solar energy available. The more irradiation the collector receives daily (kWh/m²/day), the more power it produces annually (MWh/year). We can notice no significant outliers, and the data points tend to follow a straight line. This shows consistency in the performance of photovoltaic systems, where an increase in global irradiation incidence results in a proportional increase in available energy. In other words, the system may have relatively stable efficiency regardless of daily irradiation changes.

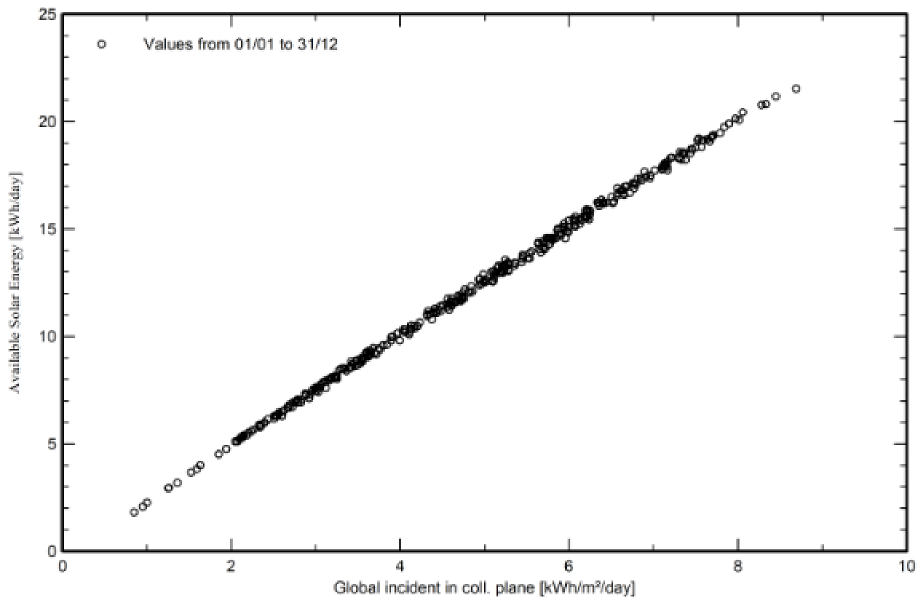

Fig. 5. Availability of solar energy per day from January-December

Fig. 6 is a step graph that depicts the relationship between energy injected into the electricity network (Power injected into grid [W]) on the horizontal axis and energy injected from the grid (Energy injected from grid [MWh]) on the vertical axis, over one year (from January 1 to December 31). This graph depicts the power injection profile of a photovoltaic system into the electrical grid over a year. On the horizontal axis, we see varying amounts of power injected into the grid in watts (W). In contrast, the vertical axis shows the cumulative energy injected into the grid in megawatt-hours (MWh). This graph shows several periods where power injection into the grid was relatively constant for a specific power range, represented by the horizontal part of the graph. Furthermore, a vertical spike indicates an increase in injected energy without a change in injected power. These spikes can occur due to the accumulated energy accumulation when the power injected into the grid is unchanged.

Gradually, uphill sections show increasing energy being injected into the grid as power increases. However, it should be noted that there is a gradual decrease in the amount of energy injected as power increases above a certain point. This indicates that at higher power levels, photovoltaic systems may inject power into the grid less frequently, or this may reflect certain times of the year when energy production is lower (such as months with less solar irradiation). Overall, these graphs provide a view of the distribution and amount of energy injected into the electrical grid by photovoltaic systems over a year and can demonstrate the system's effectiveness in injecting energy at various production levels. Additional data, such as real-time energy usage and weather conditions, would be helpful for more in-depth analysis.

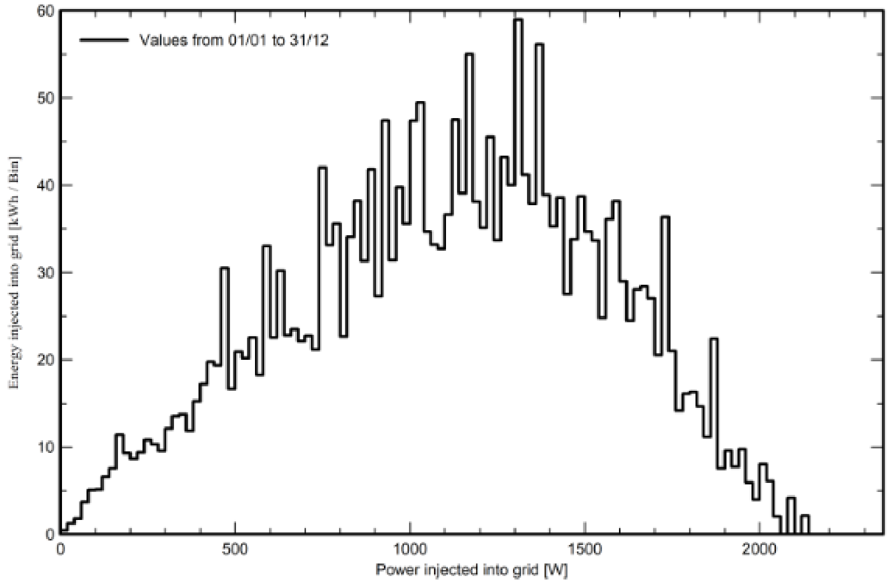

Fig. 6. Energy injection into the grid from January-December

Fig. 7 illustrates the relationship between the average temperature of the photovoltaic module and the effective global irradiance corrected for angle of incidence and shading (Effective Global, corr. for IAM and shadings [W/m²]). The graph represents the average temperature values of the module measured over some time (from 01/01 to 12/31) against the global irradiation received by the photovoltaic system. The ascending trend line indicates a positive correlation between irradiation and module temperature, which can be interpreted as an increase in global irradiation leading to a rise in module temperature. Standard test conditions (STC) indicate standard test conditions used as a reference for photovoltaic module performance. STC is usually set at a cell temperature of 25°C and irradiation of 1000 W/m² with an air mass of 1.5 (AM1.5). This is important as a basis for comparison because it shows the expected performance of the module under ideal laboratory conditions. This graph aims to show changes in module temperature caused by variations in irradiation throughout the year that can affect module efficiency and overall energy output.

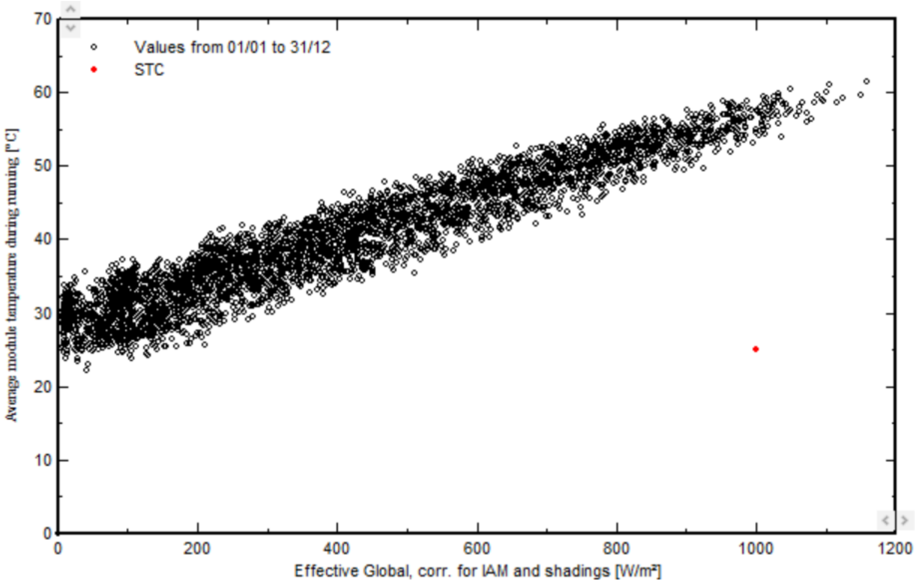

Fig. 7. Korelasi suhu modul dan iradiasi global untuk sistem fotovoltaik

Fig. 8 displays a bar graph depicting the amount of solar energy available over a year, measured in kilowatt-hours per day (kWh/day) and divided by month, from January to December. This type of data visualisation is particularly relevant in the performance analysis of grid-connected photovoltaic systems because it highlights seasonal fluctuations in solar energy generation potential. Each vertical bar shows the variation in solar energy available for a particular location in a specific month, with higher bars indicating more energy available. This graph is handy in photovoltaic system optimisation because it shows when solar panels will produce more or less energy during the year, information that is important for system capacity planning, load management, and energy storage.

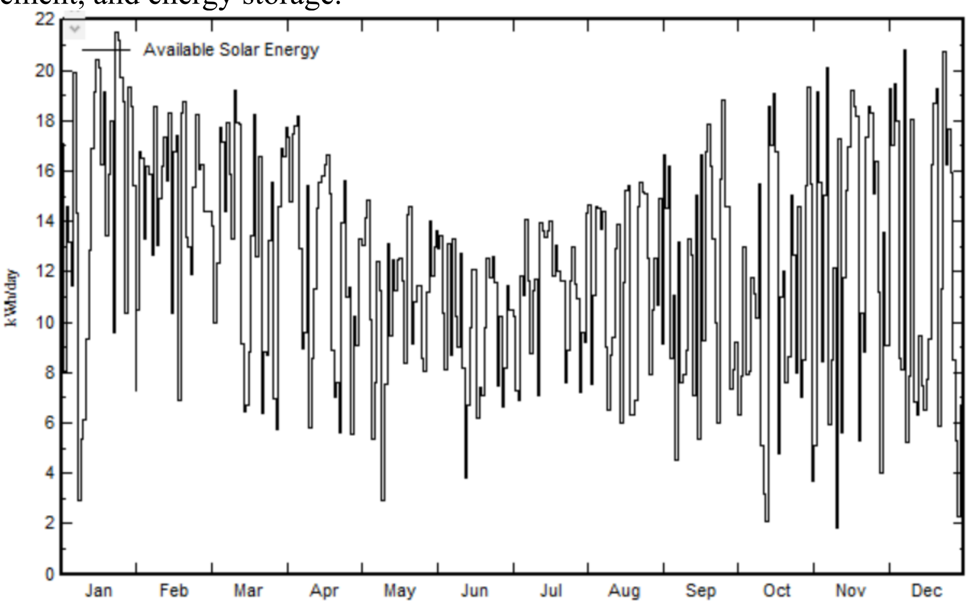

Fig. 8. Distribusi musiman energi surya tersedia untuk sistem fotovoltaik

The analysis results offer opportunities to improve the design and operation of photovoltaic systems in similar locations. For example, improving thermal insulation or using modules with higher efficiency over a broader range of operating temperatures can help reduce energy losses and increase overall output. Overall, photovoltaic systems in residential areas perform excellently and can meet most household energy needs. These results confirm the potential of photovoltaics as a sustainable energy solution in tropical regions and provide a solid basis for further development of this technology and its application in Indonesia and areas with similar conditions.

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4. Conclusion

This study shows that the grid-connected PV system at Rumah Erdiwansyah can efficiently provide most of the energy needs. Further research is required to optimise system design and storage capacity to increase the diesel fraction and achieve more sustainable energy use. Implementing a photovoltaic system like this could be an example of the application of renewable energy in tropical regions. Research conducted on photovoltaic systems connected to residential networks has provided in-depth insight into the effectiveness and efficiency of the system in meeting household energy needs. The following is a summary of the key results and conclusions of this research:

a. The photovoltaic system, with a total capacity of 3000 Wp, produced 4446 kWh of energy per year, while households used 3379 kWh per year. This indicates that the system can produce more energy than is routinely consumed by households, providing the potential for surplus power that can be injected back into the grid or stored.
b. The system's Performance Ratio (PR) reached 83.79%, indicating its efficient energy conversion level. In addition, the diesel fraction (SF) reached 55.40%, which suggests that more than half of household energy needs can be met directly from converted solar energy.
c. c. The study also revealed significant differences in energy consumption between seasons, with the highest consumption occurring in winter and the lowest in summer. This emphasises the importance of considering seasonal modulation in PV system planning and operation.
d. The results suggest that with adjustments to load management and an increase in energy storage capacity, the system can be further optimised to achieve greater energy independence and higher efficiency. They also suggest that photovoltaic systems connected to residential housing could be a valuable model for similar applications in other tropical regions with similar sunlight profiles.
e. This research's findings can help formulate more effective energy policies, especially in encouraging the adoption of photovoltaic systems in domestic environments in Indonesia and regions with similar geographical conditions. This kind of analysis supports the transition to more sustainable energy sources and reduces dependence on conventional energy.

In conclusion, grid-connected photovoltaic systems for residential homes show significant potential for generating efficient and sustainable energy. They would make an essential contribution to reducing carbon emissions and increasing energy sustainability at the household level.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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