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Design and Cost benefit Photovoltaic Rooftop for Residential in Indonesia

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Abstract. This study presents a comprehensive techno-economic assessment of residential rooftop photovoltaic (PV) systems in Indonesia. Energy output and site-specific constraints were evaluated across five design scenarios using Helioscope simulation software. Results indicate that PV systems can meet between 21.93% and 84.59% of household electricity demand, depending on system configuration. Initial load profiling identified a morning surplus of approximately 7.27 kWh, suggesting potential for battery integration. However, due to the limited surplus and high storage costs, the final design employs an on-grid configuration without battery storage. The proposed system includes 38 modules rated at 580 Wp, yielding a total installed capacity of 22.04 kWp and an estimated annual generation of 46,494 kWh. Capital expenditure (CAPEX) is projected at IDR 354.8 million, with annual operation and maintenance (O&M) costs estimated at 1.5% of CAPEX. At a residential grid tariff of IDR 1,700/kWh, the system delivers annual savings of IDR 79.04 million and a net annual cash flow of IDR 73.72 million. Over a 20-year period, assuming an 8% discount rate and 0.5% annual degradation, the investment yields a net present value (NPV) of IDR 368.98 million, a payback period of approximately 5 years, and a levelized cost of electricity (LCOE) of IDR 892/kWh. Sensitivity analysis reveals that higher electricity tariffs significantly improve economic viability; at a tariff of IDR 3,000/kWh, the NPV exceeds IDR 1.1 billion with a payback period reduced to 2.7 years. In response to Regulation of the Minister of Energy and Mineral Resources (Permen ESDM) No. 2 of 2024, which prohibits the export of excess electricity from rooftop PV systems to the grid, this study adopts a zero-export scenario in all simulations and financial modeling. These findings underscore the robust financial potential of rooftop PV systems under evolving regulatory and tariff conditions, reinforcing their role in residential energy transition strategies in Indonesia.

1. Introduction

Indonesia faces a pressing need for sustainable energy solutions, particularly in the residential sector, driven by rapid population growth and rising electricity demand. Geographically located along the equator, the country benefits from abundant solar resources, with average daily solar irradiation ranging between 4.8 and 5.0 kWh/m^2. The total solar energy potential is estimated at

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approximately 207.8 GW. In support of its energy transition goals, the Indonesian government has set a national target to achieve a 23% share of renewable energy in the primary energy mix by 2025 [1]. The design of rooftop photovoltaic (PV) systems for residential applications in Indonesia has become increasingly essential due to growing energy demand driven by both economic development and population growth. These systems offer a viable alternative energy source for households, contributing to energy security and sustainability [2]. Photovoltaic rooftop systems can boost energy supply, provide reliable, cost-effective electricity, reduce environmental impact, and lower long-term energy costs for households [3]. In Indonesia, government support has played a pivotal role in advancing the adoption of photovoltaic (PV) technology, aimed at diversifying the national energy portfolio and promoting environmental sustainability [4][5].

The integration of rooftop photovoltaic (PV) systems into buildings requires careful consideration of system design, construction, energy efficiency, and environmental impacts. Previous studies have demonstrated that distributed PV systems can significantly reduce CO_2 emissions, thereby contributing to broader sustainability goals [6]. Additionally, structural aspects such as the mounting units of solar panels are crucial to ensure both roof protection and optimal system performance [7]. Other research has highlighted the importance of site-specific factors, including geographic location, solar insolation, and system configuration, in maximizing the effectiveness of grid-connected residential PV systems [8]. Moreover, PV installations can also contribute to passive energy savings by reducing household heating and cooling loads [9]. In the context of Indonesia, where the climate is characterized by high levels of cloud cover and precipitation, these factors must be carefully incorporated into PV system design to ensure reliable and efficient energy production [10]. Several factors play a critical role in maximizing the solar energy potential of rooftop PV systems, including favorable regional characteristics such as abundant renewable energy resources, supportive government policies promoting household solar adoption, and technical considerations like roof slope and orientation[11][12][13]. The use of specialized software tools such as PVSyst and HelioScope enables detailed computer-aided design and performance optimization of PV systems. These tools facilitate the selection of optimal tilt angles, forecasting of energy production, and evaluation of key performance metrics such as yield factor and system capacity [13][14]. This study aims to assess the technical and economic feasibility of rooftop photovoltaic (PV) systems for residential buildings in Indonesia. It includes evaluating rooftop suitability, estimating solar energy output, and analyzing system performance under different load scenarios. A techno-economic analysis is conducted using indicators such as Net Present Value (NPV), payback period, and cost savings. Additionally, a sensitivity analysis on electricity tariffs is performed to understand their impact on investment viability. The study provides insights to support the adoption of residential PV systems and contribute to national renewable energy goals

2. Photovoltaic Rooftop in Indonesia

Designing and implementing photovoltaic (PV) rooftop systems for residential use in Jakarta, Indonesia, involves navigating technical, economic, and regulatory challenges to capitalize on the region's abundant solar energy potential [15]. Technical considerations include optimizing panel orientation and inclination, with a north-facing orientation at a 10° tilt providing a maximum energy output of 2497 kWh/year, compared to a south-facing orientation at a 45° tilt yielding just 1740 kWh/year [16]. A typical 2 kWp residential system requires approximately 16.8 m^2 of roof space and consists of 10 polysilicon modules rated at 200 Wp, benefiting from Jakarta's average Peak Sun Hours of over 6 $kWh/m^2/day$ [16]. Economically, the levelized cost of energy (LCOE) for

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PV systems currently surpasses electricity prices, with net present values ranging from -975 to -424 USD and payback periods of 10.3 to 12.5 years, making them less viable without financial incentives [17]. However, increasing the net-metering rate by 40% and offering a 20% installation subsidy could significantly improve feasibility, while reducing installation costs to USD 2000 could shorten the payback period to just four years [16] [17]. Regulatory support plays a crucial role, with initiatives like Government Regulation No.79 of 2014 and MEMR Policy No.49/2018 encouraging solar adoption through measures such as a 65% incentive to reduce financial burdens on users [18] [11]. However, this momentum was disrupted in 2024 following the issuance of Regulation No. 2 of 2024 by the Minister of Energy and Mineral Resources, which revoked the incentive for excess electricity generated by rooftop solar power systems and exported to the PLN grid. Nevertheless, rooftop PV systems still offer significant benefits, achieving energy savings of up to 16.02% for residential users, with grid-tied systems enhancing energy self-sufficiency to as much as 92.2%[19]. While high initial costs and long payback periods remain barriers, integrating battery storage and demand response strategies can increase self-consumption and reduce reliance on feed-in tariffs, ultimately enhancing economic viability and supporting Indonesia's transition to renewable energy [20].

3. Design Photovoltaic Rooftop

The design of photovoltaic systems in Indonesian houses begins with regional mapping to determine optimal tilt and orientation. This is followed by an energy demand evaluation based on household size, usage patterns, and appliances to ensure appropriate system sizing. Components such as panels, inverters, and Balance of System (BOS) are selected based on local market availability and performance. Grid connection requirements and necessary modifications are also planned. Site visits help assess roof conditions for optimal panel placement. In Indonesia, the optimal tilt angle ranges from 8 to 15 degrees, with azimuth adjusted accordingly. Ground-mounted panels typically face 180 degrees, while roof-mounted panels follow roof contours to maximize capacity[3].

3.1 Photovoltaic Sizing

Photovoltaic (PV) system sizing can be approached using two primary methods: Load-Based Sizing and Area-Based Sizing. The Load-Based method begins with evaluating the site's electrical load, specifically the total daily energy consumption (in kilowatt-hours, kWh) and peak power demand (in kilowatts, kW). These parameters serve as the foundation for determining system capacity. To estimate the required PV capacity, the daily energy demand is adjusted according to local solar irradiation levels, panel efficiency, and expected system losses, including those due to shading, temperature, and panel orientation. The resulting PV size reflects real-world performance expectations and ensures that the system meets the site's energy needs under typical operating conditions, rather than relying solely on standard test condition (STC) ratings.

The Area-Based Sizing method begins by estimating the photovoltaic (PV) system size based on the available installation area. This requires precise calculation of how many PV panels can be accommodated, considering panel efficiency, tilt angle, shading, and other relevant factors. The installation area is measured in square meters (m^2), while the system capacity is expressed in watts per square meter (Wp or kWp) to optimize energy generation. To support this approach, HelioScope a software tool offering advanced solar panel layout and performance simulation was utilized in this study. Its features enable accurate assessment of the maximum number of installable PV panels, facilitating optimal system sizing for the case study.

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3.2 Economic Analysis

Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCOE) are indicators that provide a comprehensive understanding of the investment's long-term profitability and cost competitiveness. The NPV quantifies the present value of net cash inflows generated over the project's lifetime, discounted at a specified rate. A positive NPV indicates that the project's returns exceed its costs. NPV can be calculated using equation below.

$$\text{NPV} = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} - C_0 \quad (1)$$

Where C_t is the net cash flow in year t, r is the discount rate, n is the project lifetime, and C_0 is the initial capital investment.

The IRR is the discount rate at which the NPV becomes zero. Due to its iterative nature, a simplified and more interpretable metric—Payback Period—is also calculated in this study.

$$\text{Payback Period} = \frac{\text{Total Investment (CAPEX)}}{\text{Annual Net Cash Flow}} \quad (2)$$

The LCOE represents the average cost per kilowatt-hour (kWh) of electricity generated by the system over its operational lifetime. It is calculated as the ratio between the total lifecycle costs and the total discounted energy production

$$\text{LCOE} = \frac{\sum_{t=0}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (3)$$

Where I_t investment expenditures in year t, M_t is operation and maintenance (O&M) cost in year t, E_t is the energy output in year t, r is discount rate, and *n* is project lifetime.

In addition, the estimated monthly savings can be calculated by subtracting the total monthly solar energy production (in kWh) from the estimated monthly electricity consumption (in kWh), and then multiplying the result by the applicable electricity tariff (in IDR/kWh). This provides a straightforward estimation of the financial benefit achieved through the use of the photovoltaic system.

4. Study Case

In this case study, the analysis began by determining the required solar panel capacity based on the available rooftop area, utilizing HelioScope software for accurate system layout and estimation. This initial step was followed by a series of simulations involving five different load scenarios to evaluate the system's performance under varying energy demand conditions. These simulations were essential in identifying the most suitable system configuration, considering both energy needs and spatial constraints. Once the optimal system setup was finalized, an economic analysis was performed to assess its financial viability. This included the calculation of Net Present Value (NPV), payback period, and projected cost savings over the system's operational lifespan. To further evaluate the robustness of the investment, a sensitivity analysis was conducted focusing specifically on electricity tariff variations. Given that electricity cost is a key factor influencing the economic benefits of solar energy systems, this analysis examined how changes in tariff rates would impact the NPV and payback period. By simulating different tariff scenarios, the analysis provides valuable insight into the potential financial outcomes under fluctuating electricity prices, helping stakeholders make more informed investment decision

4.1 Location and Building Area

The research was conducted in Jakarta, located at the coordinates 6.286608°S, 106.84001°E. The site is a three story building, and for the purposes of analysis and computation, the study has been divided into three distinct rooftop zones: Area A, Area B, and Area C. As illustrated in Figure 1.

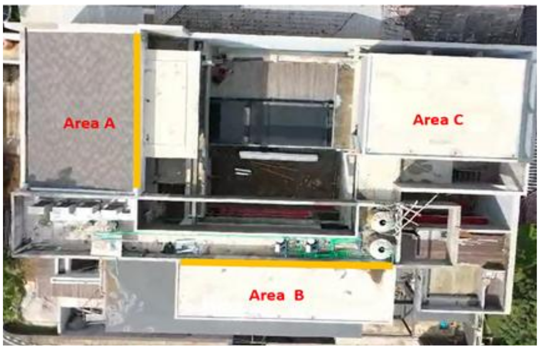

Figure 1. Rooftop Area Utilization for Solar Photovoltaics

Area A occupies a space of 6.5 × 11.22 m^2. It includes a yellow marked wall approximately 1.2 meters in height, which has the potential to cast shadows onto the rooftop surface. Additionally, the sloped nature of the roof in this section necessitates precise angle measurements to ensure accurate analysis. Area B, measuring 13.4 × 6.5 m^2, also contains a 1.2 meter high wall (denoted by the yellow line) that may obstruct sunlight and impact solar panel performance due to shading effects. In contrast, Area C covers 8.875 × 6.25 m^2 and features a flat, unobstructed surface, free from surrounding walls or other structural elements that could cause shading. This makes it an ideal location for solar energy analysis with minimal interference.

A site visit or field survey is essential to assess the rooftop's physical condition and determine the extent to which the available area can be utilized for solar panel installation. This evaluation is critical for accurately estimating the maximum number of panels that can be installed. The calculation requires matching the available space with the dimensions of the selected panel type, making the panel selection a necessary first step in the design process. In this study, 580 Wp solar panels were assumed, with the specifications detailed in Table 1.

Table 1. Photovoltaic Module Specifications

Specification	STC	NOCT
Peak power (Pmax)	580 Wp	
Dimensions	2278x1134x35mm	
Weight	28 kg	
Open circuit voltage (Voc)	51.02 V	48.46 V
Short circuit current (Isc)	14.47 A	11.68 A
Max power current (Imp)	13.69 A	10.99 A
Max power voltage (Vmp)	42.37 V	39.69 V

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4.2 System Design

Before designing a rooftop solar power system, it is essential to first determine the specific type of system to be implemented. In residential areas within urban environments, there are generally four main system configurations to consider: a 100% on-grid system with utility backup, an on-grid system without battery, an on-grid system with battery backup, and a fully off-grid system. Each of these options has its own set of advantages and disadvantages. On-grid systems without batteries are typically more cost-effective and easier to maintain but rely entirely on the utility grid. Systems with battery backup offer greater reliability during outages but involve higher initial investment and maintenance. Off-grid systems provide complete energy independence but require careful planning, larger battery storage, and higher overall costs. Therefore, selecting the most suitable system depends on various factors, including energy needs, budget, grid reliability, and the level of energy autonomy desired by the user.

4.3 Load Profile

Accurate estimation of energy consumption is essential for designing an effective solar power system and requires detailed data on electricity usage or load profiles. In buildings with limited rooftop space, even full utilization may not suffice to meet total energy demand, highlighting the need for careful system planning. Additionally, evaluating the roof's structural integrity and load-bearing capacity is critical to ensure it can safely support photovoltaic (PV) panels.Ideally, load data should be recorded over a 24-hour period to capture daily consumption patterns. However, in new buildings where electrical appliances have not yet been installed, such data is often unavailable. In these cases, an estimated load profile can be developed by identifying key appliances with the highest expected energy use. Table 2 presents the estimated load data used in this study based on this approach.

Table 2. Summary of Power Consumption by Floor

No	Summary	Equipment	Unit	Power (kW)		Total Power(kW)
				Indoor	Outdoor	
1	First Floor	AC	3	0,234	5,43	16.524
		FAN	8	0.55	0.55	0.55
2	Second Floor	AC	5	0,693	2,58	13,593
		FAN	3	0,16	0,16	0,16
3	Third Floor	AC	5	1,433	3,86	20,733
		FAN	4	0,08	0,08	0,08

Data collection indicates that air conditioning (AC) units are the primary power consumers in the building. Accordingly, this study analyzes five load scenarios focused on the operation of outdoor AC units, which represent the major energy demand on floors 1, 2, and 3. Scenario 1 assumes that all AC units across the three floors are operational. These scenarios are designed to capture variations in load profiles, which significantly influence system performance and electricity cost. Even slight changes in load demand can impact the solar system's ability to meet energy needs and affect overall efficiency. For this analysis, it is assumed that outdoor AC units operate from 08:00 to 20:00, indoor units in private rooms from 17:00 to 07:00, and family room AC units from 17:00 to 22:00. In the second scenario, all outdoor AC units are assumed to be turned off. The

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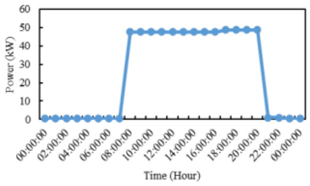
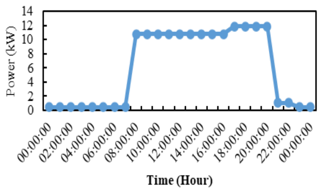
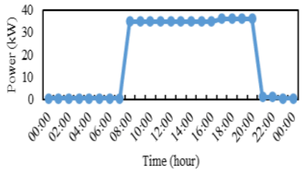
third scenario considers only the first-floor outdoor AC unit turned off, while in the fourth scenario, the second-floor unit is deactivated. Finally, the fifth scenario assumes that only the third-floor outdoor AC unit is turned off. Based on these assumptions, estimated load profiles were developed to reflect 24-hour electricity consumption patterns across all scenarios, as illustrated in Figure 2.



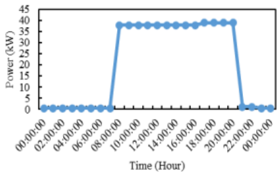
first scenario



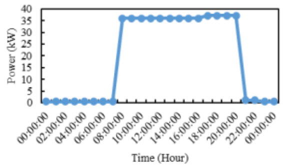
second scenario



third scenario



fourth scenario



fifth scenario

Figure 2. Load Profile for all scenario

These scenarios are not absolute, as actual electricity usage may vary depending on occupant behavior and environmental conditions. However, they provide a structured basis for analyzing the system's response to different load conditions. In Scenario 1 (all AC units active), the total load reaches approximately 48.692 kW, with a daily energy consumption of 580.98 kWh and an estimated monthly consumption of 17,429.4 kWh. Scenario 2 (all outdoor AC units off) results in a significantly reduced load of 11.83 kW, with daily and monthly consumption of 150.59 kWh and 4,517.7 kWh, respectively. In Scenario 3 (first-floor outdoor unit off), the load decreases to 12.64 kW. Scenario 4 (second-floor unit off) yields a total load of 38.982 kW, daily consumption of 503.51 kWh, and monthly consumption of 15,105.3 kWh. Finally, Scenario 5 (third-floor unit off) results in a total load of 37.122 kW, with daily and monthly energy consumption of 479.59 kWh and 14,387.7 kWh, respectively

5. Result and Discussion

By utilizing Helioscope software, the optimal number of photovoltaic (PV) modules per unit area and shadow analysis can be obtained. Figure 3 contains the detailed figure about the site where the solar PV system on the roof was installed with a supporting whole shadow analysis. Simulation results indicate that Areas A and B are affected by wall shading. This shading effect reduces the overall performance of solar panels installed in these areas. Although Area B is larger than C, the shading in Area B limits the number of modules that can be installed. As a result, Area C despite having a smaller surface area can accommodate more solar modules than Area B. Annual energy generation is a key metric used in estimating the yearly energy output, which is essential for conducting economic feasibility analysis. The system's performance ratio (PR) is calculated as

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the ratio between the actual energy generated and the maximum theoretical energy output under ideal condition.

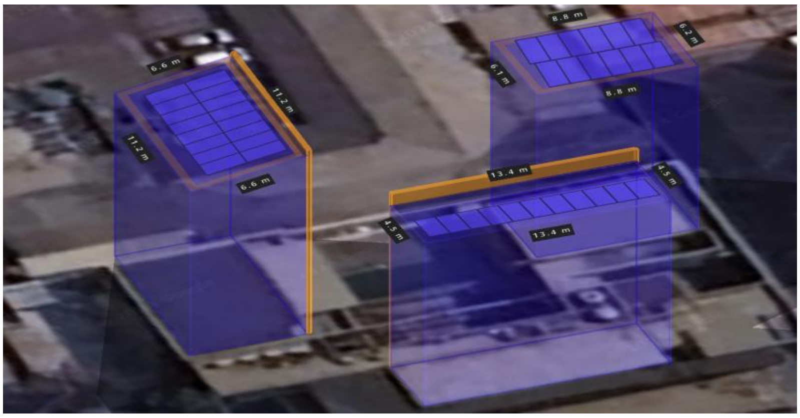

Figure 3. Simulation Result

Table 3 presents the simulation results for rooftop photovoltaic (PV) installation potential across three distinct areas of the residential building: Area A, Area B, and Area C. These areas differ in size, orientation, and shading conditions, which directly impact the number of modules that can be installed and the overall system performance. Area A, with the largest available surface area of 72.3 m^2, can accommodate up to 16 PV modules, resulting in a total installed capacity of 9.28 kWp. With a panel tilt angle of 15 degrees and a performance ratio of 76.4%, Area A is expected to generate approximately 33,530 kWh annually.

Table 3. PV System Simulation Results by Rooftop Area

Parameters	Area A	Area B	Area C
Area Size (m^2)	72.3	60.3	54.6
Number of Modules that can be Installed (Pcs)	16	10	12
Total Module Capacity (kWp)	9.28	5.8	6.96
Panel Tilt Angle (Degree)	15	10	10
Total Annual Power Output (kWh)	33.53	7.920	9.582
Performance Ratio (%)	76.4	80.2	80.2

Despite its lower performance ratio compared to the other areas, its larger module capacity yields the highest total energy output among all areas. Area B, measuring 60.3 m^2, supports 10 PV modules with a total capacity of 5.8 kWp. With a 10-degree tilt angle and a performance ratio of 80.2%, the system in this area can produce about 7,920 kWh annually. Although the installed capacity is lower than Area A, the higher performance ratio indicates better system efficiency, likely due to reduced shading or more optimal solar access. Area C, the smallest surface area at 54.6 m^2, allows for the installation of 12 PV modules totalling 6.96 kWp. Like Area B, the modules are installed at a 10degree tilt with an identical performance ratio of 80.2%. The estimated annual energy output is 9,582 kWh, which is higher than that of Area B due to the greater module

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capacity, despite similar performance conditions. Overall, the simulation highlights the trade-offs between available roof area, tilt angle, and shading conditions, all of which affect system sizing and energy production. These results serve as a foundation for selecting the optimal PV layout strategy, balancing space constraints and performance to maximize energy yield in residential rooftop applications.

Table 4 presents a summary of the rooftop photovoltaic (PV) system simulation based on the finalized design configuration. The system comprises 38 PV modules, each with a capacity of 580 Wp, resulting in a total installed capacity of 22.04 kWp. Simulation results indicate an estimated annual energy production of 29.48 MWh, corresponding to an average daily generation of 80.76 kWh. The system achieves a performance ratio (PR) of 78%, indicating the proportion of actual energy output relative to the theoretical maximum, after accounting for system losses such as temperature effects, wiring losses, and inverter inefficiencies.

Table 4. Summary of Overall PV System Simulation Results

Parameters	Result
Number of modules that can be installed	38 Modules
Module Capacity	22.04 kWp
Total power that can be obtained generated per year	29.48 MWh
Total power that can be obtained generated per day	80.76 kWh/ day
Performance Ratio	78%

5.1 Photovoltaic Output

The power output of a photovoltaic (PV) system depends on several key factors, including the number of installed panels, their orientation and tilt angle, local solar irradiance, and the time period under consideration. Figure 4 illustrates the system's power output profile over a 24-hour period. As shown, the system reaches its peak output of approximately 22 kW around midday, at 12:00 PM. One important metric for evaluating system effectiveness is the percentage of PV-generated energy relative to the total energy load. This indicates the extent to which the solar system meets energy demand and reflects the contribution of solar energy to overall consumption. Table 5 presents the detailed results, including hourly PV output, total energy load, and the share of PV energy contributing to the system's overall demand.

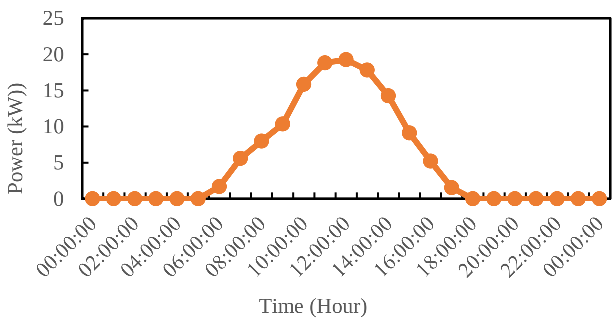

Figure 4. PV Output

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Table 5 presents a comparative analysis of household energy demand and the simulated output of the rooftop photovoltaic (PV) system under five distinct load scenarios. Each scenario reflects different daily consumption patterns, influenced by occupancy schedules and appliance usage behaviour. For all scenarios, the PV system is assumed to produce a constant daily output of 127.39 kWh, equivalent to an estimated annual generation of approximately 46,494 kWh. Scenario 1 exhibits the highest energy demand at 580.98 kWh per day, with the PV system covering only 21.93% of the load—indicating a low self-sufficiency rate due to a large mismatch between generation and demand. In contrast, Scenario 2 shows the most favourable alignment, where 84.59% of the 150.59 kWh daily load is met by PV generation, suggesting high on-site consumption and minimal reliance on the grid. Scenarios 3, 4, and 5 represent intermediate conditions with daily loads between 465.81 and 503.51 kWh, where the PV system contributes between 25.30% and 27.32% of the total energy demand. These results underscore the role of demand-side management in improving solar energy utilization and emphasize the importance of matching system design with actual load profiles to enhance efficiency and economic performance. It is important to note that these results are based on one-day simulations. In reality, both energy consumption and solar generation vary dynamically over time

Table 5. Comparison of Energy Demand and PV Output Across Load Scenarios

Scenario	Total Load (kW)	Energy Consumption (kWh)	PV Output (kWh)	Percentage of PV Production from Consumption (%)
1	48,692	580.98	127,391	21.93
2	11.83	150.59	127,391	84.59
3	36,025	465.81	127,391	27.32
4	38,982	503.51	127,391	25.30
5	37.122	479.59	127,391	26.56

Figure 5 illustrates the comparison between PV energy production and power consumption across the five load scenarios. In Scenario 2, where all outdoor AC units are turned off, the PV system meets 84.59% of the total electricity demand, with notable excess generation occurring between 07:00 and 13:00—amounting to approximately 35 kWh per day. During the early morning period (06:00–07:00), all scenarios exhibit a consistent excess production of around 7.27 kWh. In Scenario 3 (first-floor outdoor AC off), the PV system supplies 27.35% of the total load, also with a surplus of 7.27 kWh during 06:00–07:00. Scenario 4 (second-floor AC off) yields a coverage of 25.3%, with nearly all PV output absorbed by the load except for the same early morning surplus. Similarly, in Scenario 5 (third-floor AC off), PV generation covers 26.56% of demand, with an identical excess during 06:00–07:00. These findings highlight the potential for energy surplus during low-load periods and suggest the need for energy storage integration. Knowing the specific consumption profiles enables better battery sizing, which depends on the total energy to be stored and the intended duration of backup. Thus, the five scenarios serve as important references in optimizing PV system design, particularly in incorporating battery storage solutions.

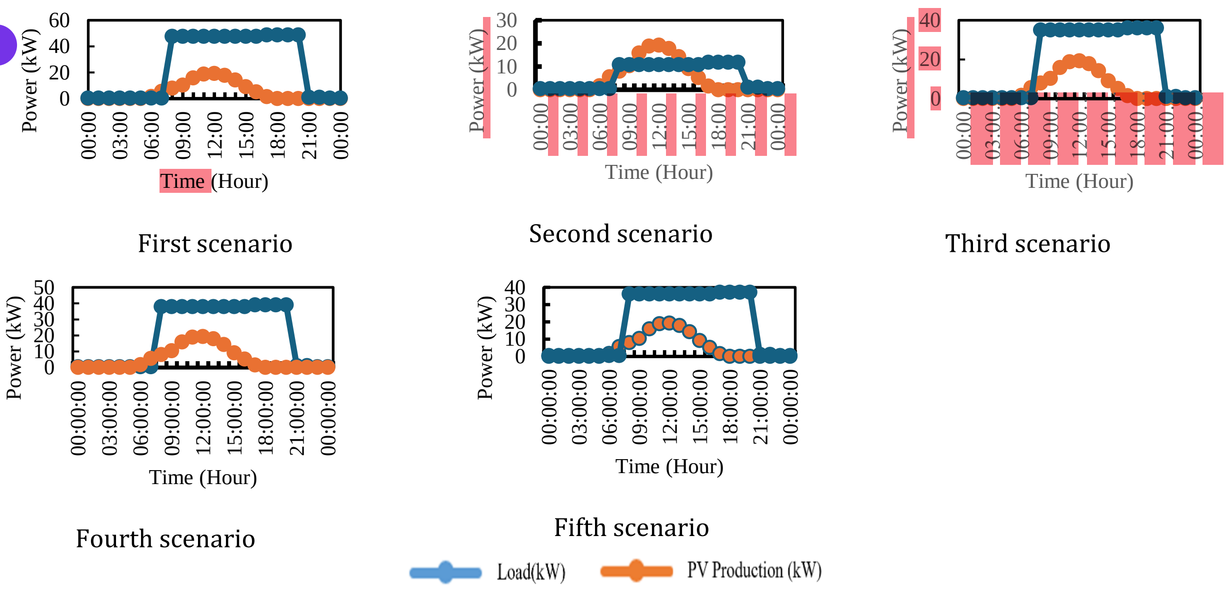

Figure 5. PV Production Vs Power Consumption

5.2 Building Rooftop Durability

Once the maximum feasible number of photovoltaic panels is determined based on available roof area, the corresponding load per unit area can be calculated. This value is essential for evaluating the structural integrity of the roof and ensuring it can safely support the additional weight of the solar installation.

Table 6 presents the weight distribution analysis of photovoltaic (PV) panels across three rooftop zones (A, B, and C) for structural evaluation of the PV installation. The assessment confirms effective surface area utilization while verifying load capacity, with Area A supporting 16 modules (1,024 kg) across 661.31 m^2, Area B containing 10 modules (320 kg) over 258.32 m^2, and Area C accommodating 12 modules (512 kg) on 317.98 m^2. Civil engineering verification indicates the rooftop's reinforced structure can safely bear these distributed loads. For comprehensive safety assurance, future evaluations should incorporate considerations of mounting systems, regional wind loads, and relevant construction standards

Table 6. Area Based Summary of PV Panel Weight and Coverage

Areas	Number of Panes (Pcs)	Area used for panels (m2)	Total Weight (Kg)
A	16	661.31	1024
B	10	258.32	320
C	12	317.98	512

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5.3 Cost Benefit

This study evaluates the economic feasibility of a rooftop photovoltaic (PV) on-grid system using three standard financial indicators: net present value (NPV), levelized cost of energy (LCOE), and return on investment (ROI) in the form of payback period. The investment includes the photovoltaic modules, inverter, mounting structures, electrical wiring, labour, and other supporting components necessary for installation and operation. Table 7 summarizes the detailed investment components for a 22.04 kWp rooftop photovoltaic (PV) system designed for residential application in Indonesia.

Table 7. Breakdown of Capital Investment for Rooftop PV System

No	Component	Details	Estimated Cost (Million IDR)
1	PV Modules	38 modules × 580 Wp (IDR 2.6 million each)	98.8
2	Inverter		55
3	Mounting Structure		40
4	LV Panel, Cable, Wiring		36
5	Other (Monitoring, Protections, Misc.)		50
6	Service (SLO+Instalation,etc)		75
	Total Investment		354.8

The total investment is estimated at IDR 354.8 million, covering all major system components and installation services. The cost of the PV modules accounts for IDR 98.8 million, representing the procurement of 38 panels rated at 580 Wp each. The inverter is estimated at IDR 55 million, while the mounting structure which ensures proper physical installation and orientation of the modules adds IDR 40 million. Electrical components, including the low-voltage (LV) panel, cables, and wiring, contribute IDR 36 million to the total. Other essential components such as monitoring systems, protection devices, and miscellaneous equipment are grouped under "Other" at IDR 50 million. Finally, service-related costs including installation labor, inspection certification (SLO), and commissioning are estimated at IDR 75 million. This comprehensive cost breakdown provides a realistic estimation of the capital expenditure required for deploying a medium-sized rooftop PV system in the Indonesian residential sector, forming the basis for the economic performance analysis. The system comprises 38 photovoltaic (PV) modules, each rated at 580 Wp, resulting in a total installed capacity of 22.04 kWp. It is estimated to produce an average of 127.39 kWh per day, equivalent to approximately 46,494 kWh annually. The total investment includes two primary cost components: the PV modules, amounting to IDR 98.8 million (IDR 2.6 million per module), and the inverter, installation, and other supporting components, estimated at IDR 256 million. This brings the total capital expenditure (CAPEX) to IDR 354.8 million. Annual operation and maintenance (O&M) costs are assumed to be 1.5% of the CAPEX. At a residential electricity tariff of IDR 1,700 per kWh, the system yields estimated annual energy savings of IDR 79.04 million. After deducting O&M costs, the net annual cash flow is approximately IDR 73.72 million, or around IDR 6.13 million per month. Using a discount rate of 8% and a project lifetime of 20 years, the Net Present Value (NPV) is calculated at IDR 368.99 million, reflecting a strong

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economic return. The payback period is estimated at approximately five years. Additionally, the Levelized Cost of Energy (LCOE) is calculated at IDR 892 per kWh, which is significantly lower than the current grid tariff highlighting the long-term cost-effectiveness and financial viability of the residential rooftop PV system.

5.4. Sensitifity Analysis

Using the same parameter, the sensitivity analysis was performed to evaluate the impact of electricity tariff increases on the financial performance of the rooftop PV system. Since electricity prices in Indonesia have the potential to increase over time, the analysis considers tariff levels ranging from IDR 1,700/kWh (base case) to IDR 3,000/kWh This assessment examines how changes in the tariff affect three key financial indicators: annual energy savings, net annual cash flow, and Net Present Value (NPV), as well as the payback period.

Table 8 presents the results of a sensitivity analysis on the impact of rising electricity tariffs on the financial performance of the rooftop PV system. As the tariff increases, both the annual energy savings and the net annual cash flow rise proportionally, resulting in a significantly higher NPV. At the base case of IDR 1,700/kWh, the NPV is IDR 368.98 million with a payback period of approximately 5 years. However, when the tariff increases to IDR 3,000/kWh, the NPV more than triples to over IDR 1.1 billion, and the payback period shortens to just under 3 years. This illustrates that the economic viability of residential PV installations is highly sensitive to electricity price fluctuations, and will become increasingly favorable if grid tariffs continue to rise in the future.

Table 8. Sensitivity Analysis

Electricity Tariff (IDR/kWh)	Annual Energy Savings (Million IDR)	Net Annual Cash Flow (Million IDR)	NPV (Million IDR)	Payback Periode (Years)
1700	79.04	73.72	368.99	5
2000	92.98	87.67	537.65	4.3
2300	106.94	191.62	706.3	3.7
2600	120.89	115.57	874.95	3.2
3000	139.45	134.2	1108.12	2.7

6. Conclusion

In this study, three rooftop regions were identified as suitable for photovoltaic (PV) installation, with an estimated capacity of 38 modules rated at 580 Wp each, resulting in a total installed capacity of approximately 22.04 kWp. However, two of the designated areas are partially affected by wall shading, necessitating careful design adjustments to minimize shadow impact. The analysis confirms that it is technically feasible to install more than 20 kWp, provided that structural load, available surface area, shading profiles, and system layout are thoroughly considered. For optimal performance and safety, system components particularly the inverter should be positioned close to the PV array to reduce power losses and prevent overheating or moisture-related degradation. Although initial simulations suggested the use of batteries to manage excess morning energy (approximately 7.27 kWh), the final system is configured as an

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on-grid design without battery storage, due to the relatively small surplus and the high cost of battery integration. The techno-economic analysis confirms that the implementation of a 22.04 kWp residential rooftop PV system in Indonesia is financially viable and highly attractive under current and projected electricity price scenarios. The system achieves a favourable NPV of IDR 368.98 million, a competitive LCOE of IDR 892/kWh well below the grid tariff and a short payback period of approximately five years. Sensitivity analysis further reveals that increases in electricity tariffs significantly enhance economic returns, reducing the payback period to as low as 2.7 years and increasing NPV to over IDR 1.1 billion. These results highlight the strong potential of rooftop solar PV as a cost-effective and sustainable energy solution for Indonesian households, especially in anticipation of future grid electricity price escalation. Therefore, broader deployment of residential PV systems can support national energy security and carbon reduction targets while offering long-term financial benefits to homeowners.

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