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Techno-economic assessment of rooftop solar photovoltaic integration for institutional energy efficiency and sustainability enhancement

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ABSTRACT
Background : This study investigates the technical and economic feasibility of an on-grid rooftop solar photovoltaic (PV) system for the Postgraduate Building of the Universitas Papua, West Papua, Indonesia. Amid rising energy demands and limited renewable energy utilization in the region, this research addresses the need for sustainable electricity solutions. **Methods:** The system was designed using Helioscope software, considering solar radiation, shading, and local climate data. The proposed configuration consists of 14 polycrystalline solar modules (320 Wp each) and one SMA Sunny Tripower 5.0 kW inverter. **Results:** Simulation results indicate that the system can produce approximately 5,660 kWh annually, covering 19% of the building's electricity consumption. The estimated initial investment of IDR 137,200,000 yields annual savings of IDR 9,617,740, resulting in a payback period of 14 years and 2 months. **Conclusion:** The findings demonstrate the viability of rooftop solar power systems for reducing energy costs and enhancing sustainability in remote areas. The project serves as a replicable model for academic institutions seeking to adopt renewable energy technologies. **Novelty:** This study provides a localized case of solar PV deployment in West Papua, contributing empirical insights to regions with limited renewable energy integration and offering a practical approach to energy transition in underserved areas.

KEYWORDS: rooftop solar pv; on-grid system; renewable energy; helioscope; west papua.

1. Introduction

The demand for electrical energy is a fundamental driver of progress in modern Indonesian society, underpinning essential services across the industrial, commercial, and residential sectors (Rehiara et al., 2023). In line with its developmental agenda, Indonesia continues to witness a rapid increase in energy consumption, fueled by population growth, urbanization, industrial expansion, and rural electrification efforts. To meet this growing demand, the government has long relied on PT PLN (Persero), a state-owned electricity utility responsible for generation, transmission, and distribution, in accordance with Law No. 15 of 1985 (Nugraha et al., 2025). However, PLN's capacity expansion efforts have not kept pace with rising demand, especially in remote regions, leading to persistent energy shortfalls and an electrification rate that falls below national targets (Rehiara et al., 2025). Therefore the demand for electricity is growing more rapidly than the supply, and the national electrification ratio was still at 80.4% in 2013, meaning that 19.6% of Indonesia's population had not yet gained access to electricity (Sinaga, 2023). According to PT. PLN, over the past five years, the growth rate of power plant development, at 6.5% per year, has not been able to keep up with the electricity demand growth rate of 8.5%. This lag is due to

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various constraints, such as land acquisition and provision for power plants, among other issues (Duka et al., 2018; Handayani et al., 2024).

This disparity is particularly evident in the outer provinces of Indonesia, such as West Papua, where the extension of grid infrastructure is challenged by difficult terrain, low population density, and logistical constraints. The national electrification ratio stood at only 80.4% in 2013, which implied that around 19.6% of Indonesia's population lacked access to electricity at that time. Despite improvements in recent years, these challenges persist (Sinaga, 2023). Moreover, PT PLN reported that over the past five years, the average annual growth in power plant development was approximately 6.5%, while the electricity demand grew by 8.5%, further widening the supply-demand gap (Duka et al., 2018; Handayani et al., 2024). The limited availability of land for constructing new power plants, particularly in densely populated or geographically constrained regions, has further hampered efforts to meet demand through conventional infrastructure expansion.

In parallel with these structural constraints, Indonesia's heavy dependence on fossil fuels—particularly coal and petroleum—for electricity generation has raised significant environmental and sustainability concerns. The adverse impacts of fossil fuel combustion, including greenhouse gas emissions, environmental degradation, and public health risks, are becoming increasingly apparent. Additionally, Indonesia's fossil fuel reserves are finite and diminishing, prompting policymakers to explore and invest in more sustainable energy alternatives. In response, the Indonesian government has adopted a series of policies to promote renewable energy, especially solar power, as part of its strategy to transition to a low-carbon energy system (Rachmanto et al., 2023).

Solar energy, in particular, offers a compelling solution for Indonesia due to the country's high solar irradiation levels and widespread availability of rooftop space, especially in urban and semi-urban settings. The development of rooftop solar photovoltaic (PV) systems—particularly in On-Grid configurations—has gained traction as a decentralized energy solution that can complement the national grid and improve energy access (Poornima et al., 2025). These systems are directly connected to the local distribution network, allowing excess electricity generated during peak sunlight hours to be fed back into the grid, thus enhancing system reliability and reducing net electricity consumption. Research affirms the technical feasibility and environmental benefits of rooftop solar systems in diverse geographical contexts times (Kapsalis et al., 2024; Tan et al., 2024; Wei et al., 2024).

From a techno-economic perspective, the deployment of rooftop solar PV systems has been shown to reduce electricity costs, increase energy independence, and improve power system resilience. Research demonstrates that the integration of rooftop solar systems in buildings can significantly reduce peak load demand, lower electricity bills, and support environmental objectives (Wang et al., 2023; Yao & Zhou, 2023; Zhang et al., 2023). For instance, a report show that on-grid rooftop solar systems in office buildings have achieved grid dependency reductions of up to 30%, resulting in substantial operational cost savings (Ariawan et al., 2021). These benefits are further amplified by technological advancements in solar modules, inverter systems, and smart metering, which improve energy efficiency, monitoring accuracy, and overall system performance.

Despite these promising developments, the penetration of rooftop solar PV systems remains limited in remote and underdeveloped regions of Indonesia, such as West Papua. In these areas, the implementation of renewable energy technologies is often constrained by a lack of infrastructure, limited policy incentives, insufficient technical capacity, and unfamiliarity with renewable technologies. Moreover, the region's unique climatic conditions—characterized by high humidity, variable solar irradiance, and dense vegetation—necessitate localized studies to evaluate the performance and viability of solar PV systems under site-specific environmental conditions (Rehiara & Setiawidayat, 2022).

To address these regional disparities and facilitate the adoption of renewable energy in under-electrified areas, system design must be carefully tailored to local architectural, climatic, and economic contexts. This is where simulation tools such as Helioscope play a vital role. Helioscope is a state-of-the-art PV system design software that enables users to simulate and optimize system performance based on input parameters such as roof orientation, tilt angle, shading conditions, and local solar irradiation profiles (Arnoos et al., 2024; López-Aguilar et al., 2025; Mijbal & Mohammed, 2025). By leveraging detailed 3D modeling and advanced performance algorithms, Helioscope facilitates the accurate estimation of energy yield, system losses, and potential cost savings. Helioscope-based simulations can help maximize energy capture, minimize performance losses due to partial shading or suboptimal orientation, and support the strategic placement of system components (Kortetmäki et al., 2024; Mahdi & Hacham., 2025; Virgiano et al., 2022).

This study adopts Helioscope as a core tool for designing a rooftop solar PV system for the Graduate Building at the Universitas Papua. By conducting a detailed techno-economic analysis using actual building parameters and local solar data, the study aims to demonstrate the technical feasibility and cost-effectiveness of rooftop solar installations in a region that has received limited research attention to date. This effort builds on prior work emphasize the importance of context-sensitive system modeling in achieving realistic performance estimates (Maity et al., 2024; Rafi et al., 2025). The design process incorporates architectural characteristics, system layout constraints, inverter placement, and expected weather profiles to ensure that the simulation reflects real-world conditions as closely as possible.

A review of the literature reveals a research gap in the deployment of rooftop solar PV systems in Papua, where empirical studies are sparse, and renewable energy development lags behind other Indonesian regions. While various studies have explored rooftop PV feasibility in major urban areas—often supported by strong regulatory frameworks and favorable policy incentives (Iskandar et al., 2023; Pramadya & Kim, 2024)—these findings may not be directly transferable to less developed regions. Factors such as electricity pricing, grid reliability, policy support, and user behavior differ significantly between regions, affecting both the financial viability and social acceptance of rooftop solar technologies. Therefore, a localized, data-driven approach is essential for developing practical and replicable solutions for regions like West Papua (Rehiara & Setiawidayat, 2022).

The integration of rooftop solar systems also resonates with broader sustainability goals under the Circular Economy (CE) framework. The Ellen MacArthur Foundation (2020) outlines the energy transition as one of the most critical pillars of circularity, emphasizing the importance of clean energy, system optimization, and the regenerative use of resources. Similarly, the UNEP's 2021 report on Circular Economy and the Energy Sector stresses that renewable energy technologies not only decouple emissions from growth but also form the backbone of circular infrastructure in cities and institutions. Incorporating CE principles in energy systems involves enhancing energy efficiency, reducing emissions, maximizing resource use (e.g., rooftops), and enabling reuse or recycling of system components. Solar PV systems, when planned in alignment with CE principles, promote long-term sustainability through modular design, longer lifecycle, and reduced environmental footprints (Mahdi et al., 2024). Yet, empirical applications of CE in renewable energy in remote settings like Papua are sparse.

The novelty of this study lies in its integration of high-resolution simulation modeling with a regionalized techno-economic feasibility assessment for a rooftop solar PV system in West Papua—an area currently underrepresented in solar energy research. Unlike existing studies that focus on national policy or aggregate demand projections, this research offers a micro-level case study using real building data, architectural constraints, and local environmental inputs. The study contributes to the scientific literature by addressing a critical gap: the lack of empirical evidence and localized models for rooftop solar PV systems in geographically and socioeconomically disadvantaged regions of Indonesia. By focusing on the Graduate Building of the Universitas Papua, the study not only evaluates technical performance and economic benefits but also proposes a scalable model for similar public and institutional buildings in remote areas.

Additionally, this study introduces a multidisciplinary framework that combines energy modeling, economic analysis, and infrastructure assessment. It incorporates the latest performance metrics for PV modules and inverters, considers seasonal solar radiation variation, and evaluates potential grid interactions under On-Grid system configurations. The findings are expected to inform local decision-makers, university administrators, and government agencies on the practical steps required for implementing solar energy projects in the region. The study also complements national efforts to increase renewable energy adoption under Indonesia's National Energy Policy (*Kebijakan Energi Nasional*), which targets 23% renewable energy contribution by 2025.

The research objective is to design an optimized rooftop solar photovoltaic system for the Graduate Building at the Universitas Papua using Helioscope software and to evaluate its energy-saving potential, grid integration prospects, and economic viability. The hypothesis is that the proposed system can reduce electricity costs by at least 20%, improve energy security, and serve as a prototype for broader renewable energy applications in Papua. The study also seeks to document the methodology in a way that enables replication in similar climatic and infrastructure contexts. It is anticipated that the findings will validate the suitability of rooftop solar PV systems for underdeveloped areas, contribute to the body of knowledge on context-specific renewable energy design, and offer strategic insights for achieving Indonesia's sustainable energy goals.

2. Methods

2.1 Research location and load profiles

The research location is the Postgraduate Building of Unipa, located on Jalan Gunung Salju, Amban, Manokwari, West Papua Province, Indonesia. Geographically, the Postgraduate Building is situated in the Southern Hemisphere, with coordinates at Latitude 0°50'09" South and Longitude 134°04'2" East. The Postgraduate Building has one rooftop that holds potential for solar module installation. According to the rooftop PV installation guidelines in Indonesia, to avoid shading, buildings located south of the equator are ideally suited for solar modules to be installed facing north. This is because rooftops facing north tend to produce more energy due to receiving more sunlight.

This study utilizes the load data of the Postgraduate Building of Unipa, recorded during daily office operating hours. The building's hourly load data was obtained through primary data collection at the Postgraduate Building of Universitas Papua, which is supplied by PLN with an installed capacity of 33,000 kVA, 3-phase, under the medium business tariff category (P-1/TR). The data collected is primary data obtained through a monitoring method, where the kWh meter at the Postgraduate Building of Unipa functions as a monitoring tool to record electricity consumption.The highest recorded load usage is shown in Table 1.

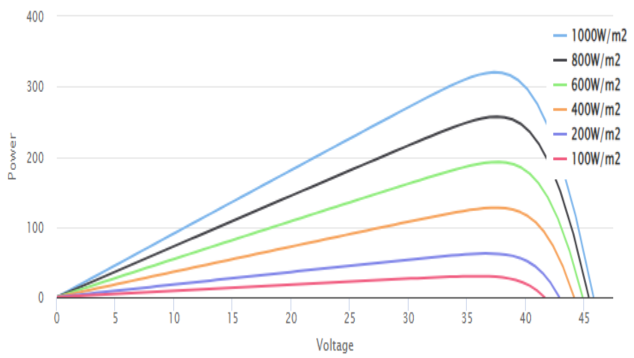
Table 1. Load profiles

Day	Time	Power (kW)
Monday	12:00	4.12
Tuesday	12:00	5.25
Wednesday	12:00	2.33
Thursday	12:00	5.63
Friday	12:00	6.94
Saturday	12:00	4.48
Sunday	12:00	3.38
Total		32.12
Average		4.59

2.2 System components

The planning of the rooftop photovoltaic (PV) system on the Postgraduate Building refers to the installed power capacity of PT. PLN (Persero), in accordance with applicable regulations. The installed capacity of the PV system must not exceed the installed power provided by PT. PLN (Persero). The Postgraduate Building has an installed capacity of 33,000 VA; therefore, the planning is carried out based on this installed power in order to maximize the output of the PV system. Based on this consideration, the solar module selected for this study is a polycrystalline silicon module of the brand Tellmax TDM-PD 4 320 (May 6), manufactured by Trina Solar. The specifications and power curve of the Tallmax-type solar module, Tellmax TDM-PD 4 320 (May 6), Trina Solar, are presented in Table 2.

Table 2. Solar module specifications



Data	STC*	NOCT**
Peak Power Watts (Wp)	320	237
Maximum Power Voltage (V)	37.1	34.3
Maximum Power Current (A)	8.63	6.92
Open Circuit Voltage (V)	45.5	42,1
Short Circuit Current (A)	9.15	7,39

* Standard Test Condition; **Nominal Operating Cell Temperature

In this study, the type of inverter used is the SMA Sunny Tripower 5,000, which is commercially available and certified to facilitate maintenance. The inverter selected is the SMA brand, Sunny Tripower 5.0 TL-US, with a power rating of 5.0 kW. The specifications of the inverter used in this study are shown in following table 3.

Table 3. Inverter specifications

Technical data	SunnyTripower 5.0
Max. usable DC power	9000 W
Max. DC voltage	850 V
Rated MPPT voltage range	215 V to 800 V
MPPT operating voltage range	580 V
Min. DC voltage / start voltage	125 V
Number of MPP tracker inputs	1
Max. input current / per MPP tracker input	12 A/18 A
AC nominal power	5000 W
Max. AC apparent power	5000 VA

2.3 Otimal tilt angle and payback period

The optimal roof tilt angle must be considered in the design of a rooftop PV system in order to maximize solar irradiation potential. The optimal roof tilt angle can be calculated, using following equation (Ariawan et al., 2021).

$$\alpha = 90^0 - lat - \delta \quad \text{(Eq. 1)}$$

$$\beta = 90^0 - \alpha \quad \text{(Eq. 2)}$$

Where β is the optimal roof tilt angle, lat is the latitude of the solar panel installation location (in degrees), and δ is the solar declination angle. Simple payback refers to the duration required for the cumulative cash flow difference between the base case system and the optimized system to turn positive. In other words, the payback period is the time it takes to recover the additional investment costs incurred by the optimized system compared to the reference system. This can be formulated as follows (Rachmanto et al., 2023).

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$$PP = \frac{CoI}{ACI} \quad \text{(Eq. 3)}$$

Where *PP* is the payback period, *CoI* is the cost of investment, and *ACI* is the annual cash inflows.

2.4 Initiative selection and comparative analysis framework

To ensure transparency and reproducibility in this study, the selection of rooftop solar photovoltaic (PV) initiatives followed a systematic process grounded in relevance, data availability, geographic comparability, and institutional context. The primary focus was the rooftop solar PV system proposed for the Postgraduate Building at Universitas Papua. However, to contextualize and validate the feasibility of this initiative, the study also incorporated a comparative analysis involving similar installations across Indonesia and Southeast Asia. These included case studies of rooftop solar systems deployed in public institutions, especially universities or government buildings, which often share operational characteristics and energy usage patterns.

The initiatives selected for comparison were required to meet several criteria. First, they had to involve grid-connected rooftop solar PV systems, ideally within institutions or public facilities that mirror the building typology and energy profile of the Postgraduate Building. Second, data on technical and economic performance had to be accessible—either from peer-reviewed literature, national energy project databases, or publicly available project documentation. Third, preference was given to projects located in remote or under-electrified regions, particularly those experiencing infrastructure and climatic conditions comparable to those of West Papua. This ensured that comparisons remained meaningful within the unique geographic and socio-economic context of the study site.

Comparisons among the selected initiatives were carried out across three main dimensions: technical performance, economic feasibility, and contextual fit. Technical performance parameters included system capacity in kilowatt-peak (kWp), annual energy generation in kilowatt-hours (kWh), and system performance ratios. Economic feasibility was evaluated using total investment costs, and estimated payback periods, all normalized where necessary (e.g., IDR/kWp or savings per square meter). The contextual fit was examined by considering regional climate, grid stability, energy tariffs, and institutional consumption patterns. This multi-dimensional approach ensured that the comparison captured both quantitative and qualitative aspects of feasibility.

The framework for this comparative analysis was adapted from renewable energy assessment guidelines developed by the Ellen MacArthur Foundation and policy frameworks outlined by the United Nations Environment Programme (UNEP). These global references emphasize the importance of localized, context-sensitive evaluation for renewable energy deployment within the broader principles of a circular economy and sustainability transitions. By aligning with these established methodologies, the study enhances its relevance to global sustainability goals while maintaining a strong focus on the specific conditions in Papua. This structured approach strengthens the validity of the findings and supports the development of practical recommendations for future rooftop solar implementations in similar settings.

3. Results and Discussion

3.1 Technical performance

This section presents the simulation results and key findings related to the rooftop solar power system design for the Graduate Building at the Universitas Papua. The simulation, conducted using Helioscope, provided insights into energy production, efficiency, and the potential for energy savings. The research successfully designed a rooftop photovoltaic layout using Helioscope software, determining optimal panel placement on a 667 m^2 roof surface with optimal roof tilt angle about 30°. The chosen configuration consisted of a flush mount racking system and polycrystalline Tellmax TDM PD-4 320 Wp modules connected in one series string. Electrical parameters showed each string operated at 519.3 V and 8.63 A, remaining safely below the inverter's maximum input ratings of 850 V and 12 A, thus validating the electrical compatibility of the system components.

The Tallmax TSM-PD solar modules used in this study are known for their high efficiency under various conditions, which gives the current design an edge over traditional systems. Using advanced solar panels can improve efficiency by up to 10% (Virgiano et al., 2022), especially when combined with inverters like the SMA Sunny Tripower, which minimize losses during the conversion from DC to AC. This combination is likely a key factor in the system's enhanced performance.

The design and simulation of a rooftop solar power plant (PLTS) at the Postgraduate Building of Universitas Papua yielded significant insights into the system's performance and economic feasibility. With an installed capacity of 4.48 kWp comprising 14 polycrystalline solar panels, the system achieved a total annual energy production of 5,660 kWh. This output corresponds to a 19% annual reduction in electricity consumption and utility expenses, given in following table. This result is marginally higher than the one found in a nearby location (Workala et al., 2023).

Table 4. Main findings

Time (hour)	Power Consumption (kWh)	PV System Output (kWh)	Power Difference (kWh)	Percentage of Energy Savings (%)
06:00-07:00	3.77	0.26	3.50	7%
07:00-08:00	3.73	1.03	2.69	28%
08:00-09:00	5.07	1.55	3.51	31%
09:00-10:00	7.02	1.90	5.12	27%
10:00-11:00	8.20	2.11	6.09	26%
11:00-12:00	8.36	2.17	6.19	26%
12:00-13:00	8.60	2.05	6.55	24%
13:00-14:00	8.35	1.77	6.58	21%
14:00-15:00	8.11	1.35	6.75	17%
15:00-16:00	7.73	0.84	6.89	11%
16:00-17:00	6.50	0.39	6.11	6%
17:00-18:00	4.95	0.10	4.85	2%
Daily	80.39	15.51	64.881	19%
Annual	29,342	5,660	23,682	19%

Simulations using Helioscope showed the system operated within the recommended voltage and current thresholds. Furthermore, the primary energy loss was due to temperature, while losses from shading, clipping, and wiring remained negligible. Based on data from the Helioscope simulation using the TMY (Typical Meteorological Year) Weather Dataset, the average ambient temperature at the Postgraduate Building over the year is 28.4°C, while the average temperature of the solar modules is 50.4°C. The highest power loss is caused by temperature at 16.6%, whereas the lowest losses are due to clipping at 0.0%, shading at 0.0%, and wiring at 0.5% as seen in Fig. 2.

Based on simulated data, hourly energy production figures, supported by temperature and irradiance profiles, showed a peak generation of 2.17 kWh occurring between 11:00 and 12:00. The system reached a daily average production of 15.51 kWh and an annual output of 5,660 kWh. Energy losses were quantified with thermal losses accounting for 16.6% and others, such as shading and wiring, remaining under 0.5%. These results affirm the system's efficiency and suitability for the building's demand profile.

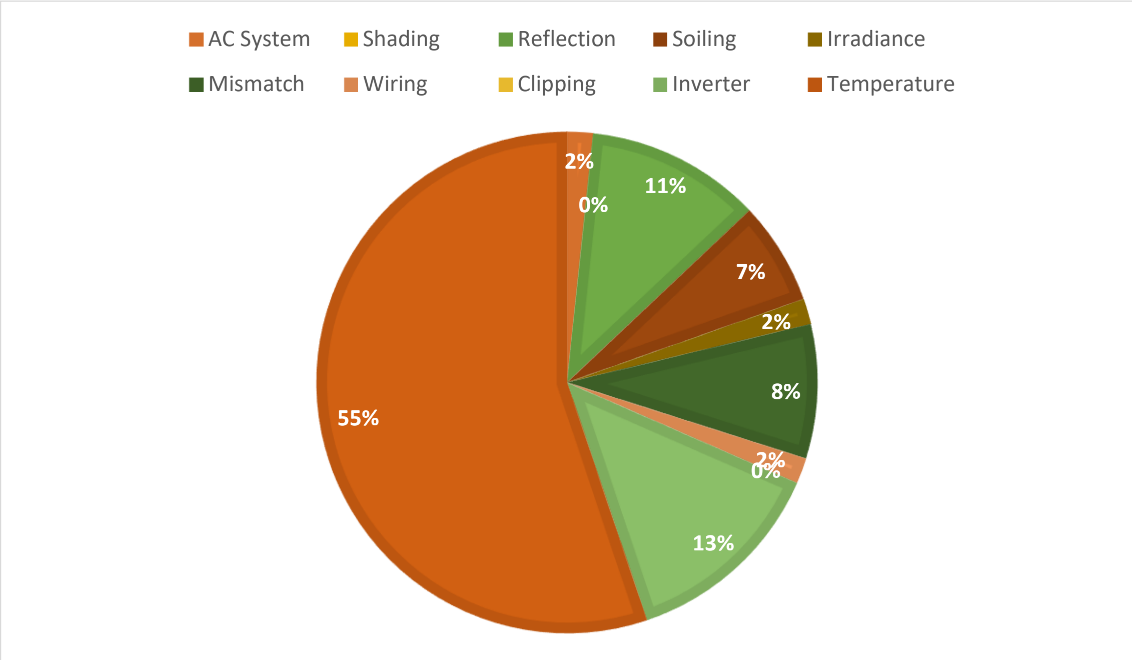

Fig. 2. Loses summary in the rooftop solar power plant

The simulation accounted for shading due to nearby structures and natural obstructions. Fortunately, the rooftop's orientation and lack of significant shading obstructions ensure that the system operates near its optimal efficiency. The total annual shading loss was minimal, recorded at 0.5%, largely due to the strategic positioning of solar modules on the rooftop's northern side. Fig. 3 provides a layout of the rooftop solar installation as modeled in Helioscope.

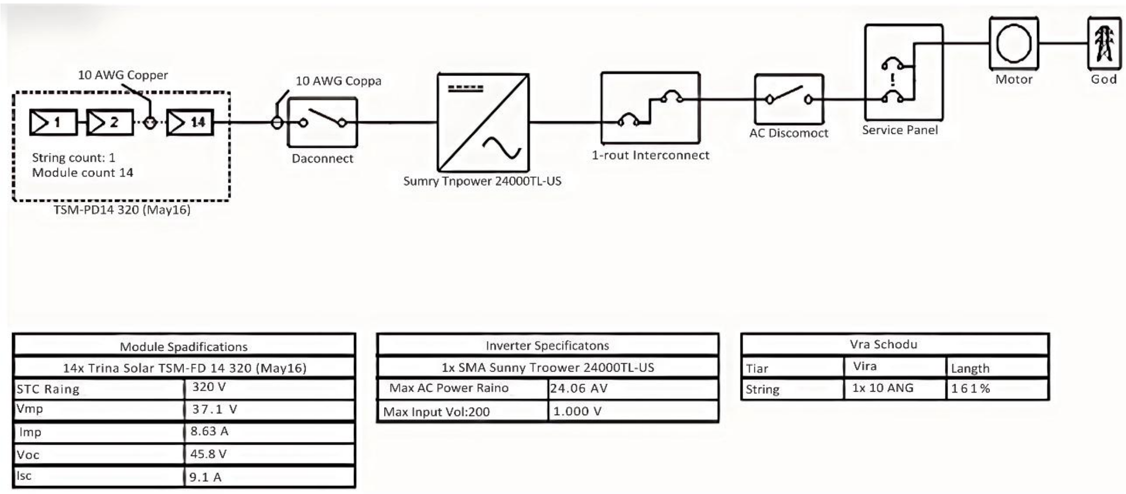

Fig.3. Rooftop solar installation layout design with helioscope simulation

3.2 Economical analysis

In Indonesia, total cost to install a 1 kWp rooftop PV system is about IDR 24,500,000 (Kual et al., 2023). Therefore, the planning capacity of Postgraduate Building of Unipa is about 4.48 kWp at can reach total initial investment amounts to IDR 109,760,000. With maintenance cost 1% per year, the total maintenance cost over the period a lifespan of 25 years is about IDR 27,440,000. Then total investment cost is the summation of both cost about IDR 137,200,000.The above cost analysis follows the provisions of Minister of Energy and Mineral Resources Regulation No. 28 of 2016 concerning electricity tariffs supplied by PT. PLN (Persero). The electricity tariff for office usage under tariff group P1 is IDR 1,699.53

per kWh. With annual energy production = 5,660 kWh, the annual monetary value of energy produced reach IDR 9,617,740.

Through a comprehensive economic analysis of the rooftop PLTS installation. With an investment cost of IDR 137,200,000 and annual savings on electricity bills amounting to IDR 9,619,743 the system demonstrated a payback period of approximately 14 years and 2 months. This analysis, based on prevailing electricity tariffs of IDR 1,699.53/kWh, confirms the economic viability of the solar power installation. Maintenance costs, calculated as 1% of the investment per year, also align with sustainable operational feasibility over a 25-year system lifespan. Research by Ariawan et al. (2021) on similar rooftop solar systems in other parts of Indonesia has shown that typical installations in urban areas yield energy savings of around 20-25%. In contrast, the current system for the Graduate Building at the Universitas Papua achieves an estimated 27% savings, showcasing an improvement over previously documented outcomes. The higher efficiency is attributed to the system's optimized configuration, as well as the unique climatic conditions in West Papua.

3.3 Role of informal sector and local communities in advancing circular economy

In addition to technical and financial considerations, an often-overlooked but critical dimension in Indonesia's energy transition and circular economy (CE) framework is the role of the informal sector and local communities. This is especially relevant in Papua, where institutional capacity and formal infrastructure are limited. Informal actors such as local electricians, maintenance workers, and solar entrepreneurs often step in to fill service gaps left by government or utility providers. These actors can serve as enablers of decentralized energy solutions if given proper support and recognition.

The Ellen MacArthur Foundation emphasizes that local community engagement is essential for the long-term success of CE implementation, particularly in remote areas where resource circulation and maintenance depend on contextual knowledge and shared stewardship. Moreover, the United Nations Environment Programme (UNEP) underlines the importance of inclusive frameworks that empower informal workers, especially in waste and energy sectors. This aligns with grassroots efforts in many Indonesian provinces where community-led solar initiatives are already emerging.

In this context, future solar PV deployment in regions like West Papua could benefit from capacity-building programs targeting these informal stakeholders. Such programs could include technical training, small-scale financing schemes, and co-management strategies where local communities co-own and maintain the systems. This not only enhances system reliability but also builds local ownership, contributing to CE principles by extending the useful life of infrastructure and reducing reliance on external service providers.

Therefore, integrating CE principles into solar PV deployment must go beyond system efficiency and economic return (Mahdi et al., 2024). It must include socio-cultural adaptation, empowerment of local actors, and promotion of inclusive governance. These dimensions are critical in ensuring that energy transitions in Indonesia are not only green and cost-effective but also just and participatory.

3.4 Discussion

The results of this study demonstrate that the implementation of a 4.48 kWp rooftop photovoltaic system can effectively reduce the annual electricity consumption of the Postgraduate Building at Universitas Papua by approximately 19%. This reduction translates into a significant decrease in electricity costs, proving the technical and economic feasibility of such a system in a tropical, remote setting like West Papua. Simulation results based on Helioscope modeling show consistent performance across different operational hours, with peak energy savings reaching up to 31% during optimal irradiance periods (08:00–09:00). These savings gradually decrease throughout the day, aligning with the expected solar generation curve. The system achieved an average daily production of 15.51 kWh, with a total annual output of 5,660 kWh.

The most substantial system losses stemmed from temperature effects, which accounted for 16.6% of the total energy loss. However, losses due to shading, wiring, and clipping were minimal—recorded at 0.5% or less—demonstrating an efficient system layout and appropriate component selection. The strategic orientation of the solar panels toward the north (as recommended for installations south of the equator) contributed significantly to these minimal losses. Financially, the system exhibits long-term sustainability. The total investment cost of IDR 137,200,000—including installation and maintenance over a 25-year lifespan—is balanced by annual energy savings of IDR 9,617,740. This yields a payback period of approximately 14 years and 2 months. While this payback period is relatively long, it remains within acceptable margins for institutional investments and offers a sustainable alternative to fossil-fuel-based electricity.

The use of simulation software such as Helioscope enabled precise system design, including optimal module positioning and performance prediction under local climatic conditions. This methodology ensures reliability and replicability for similar projects in regions with comparable environmental characteristics. In comparison with previous studies (e.g., Ariawan et al., 2021), which documented 20–25% energy savings in urban contexts, the current system achieved comparable performance, despite the geographical and infrastructural constraints of West Papua. The slightly higher efficiency observed may be attributed to lower urban shading and the stable climatic patterns in the region.

From a broader perspective, this study provides evidence supporting the scalability of rooftop PV systems in educational and institutional buildings across Indonesia. By reducing operational costs and dependency on centralized grid systems, such initiatives contribute directly to the nation's renewable energy targets and Sustainable Development Goals (particularly SDG 7: Affordable and Clean Energy). Nonetheless, this research has certain limitations. First, real-world performance may be affected by unforeseen factors such as dust accumulation on panels, aging of inverter components, or grid fluctuations, none of which were modeled in the simulation. Second, the static electricity tariff used in the financial analysis does not account for potential regulatory or market changes over the project’s lifespan. Third, the load profile used in this study was based on fixed office hours and did not capture dynamic load variations that could impact self-consumption ratios and energy export potentials.

Future work should address these limitations by incorporating dynamic load modeling, real-time monitoring systems, and hybrid configurations (e.g., integration with battery storage or diesel backup systems). Additionally, exploring government incentives or community-based financing models could help reduce the initial investment burden and promote wider adoption in underserved areas. In conclusion, the system designed for the Postgraduate Building at Universitas Papua not only meets its intended energy-saving goals but also sets a precedent for similar institutions seeking to transition toward sustainable energy practices. The findings serve as a valuable reference for policymakers, academics, and practitioners aiming to implement cost-effective and environmentally responsible energy solutions in remote and tropical regions.

4. Conclusions

This study successfully designed and evaluated the technical and economic feasibility of a 4.48 kWp rooftop solar photovoltaic (PV) system installed on the Postgraduate Building at Universitas Papua. The findings highlight the system’s capacity to generate approximately 5,660 kWh of electricity annually, resulting in a 19% reduction in grid-supplied electricity consumption. This translates to annual cost savings of approximately IDR 9,617,740, validating the system’s potential to contribute meaningfully to institutional energy efficiency. The total investment required for the system—including installation and 25 years of maintenance—is estimated at IDR 137,200,000. With a payback period of 14 years and 2 months, the project demonstrates strong economic viability within the context of a public educational institution. Moreover, the use of Helioscope simulation software ensured accurate system sizing, efficient layout, and reliable performance forecasting under local environmental conditions.

In addition to technical and financial feasibility, the study highlights the broader replicability of such decentralized solar installations in remote and underserved regions like West Papua. The application of Helioscope simulation enabled accurate system sizing and reliable performance predictions, ensuring that environmental factors were effectively considered in the system design. A more comprehensive roadmap for scaling rooftop solar adoption in Indonesia should not only emphasize policy reforms and technical innovation but also integrate informal sector participation and local community engagement. Waste pickers, local technicians, and grassroots cooperatives could be mobilized to support system maintenance, awareness campaigns, and user engagement. Furthermore, financial strategies such as green loans, government subsidies, or community-based financing schemes should be explored to lower capital barriers for similar institutions and households.

To strengthen implementation, future research should include performance monitoring of the installed system, integration with storage or hybrid backup options, and adaptive planning to accommodate policy or tariff changes. These strategies will help ensure both economic resilience and environmental sustainability. Ultimately, this study contributes to Indonesia's renewable energy roadmap and offers a viable model for energy transition in the education sector. By promoting clean, affordable, and inclusive energy solutions, it supports the advancement of Sustainable Development Goal 7 (Affordable and Clean Energy) and strengthens institutional pathways toward a low-carbon future. Ultimately, this research contributes to national and global sustainability goals by promoting clean energy adoption in the education sector, supporting Indonesia's renewable energy roadmap, and aligning with Sustainable Development Goal 7: Affordable and Clean Energy.

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Author Contribution

The authors S.D.A., A.B.R., Y.R., contributed to the literature search, interpretation, writing, and proofreading of the manuscript. The author have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

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