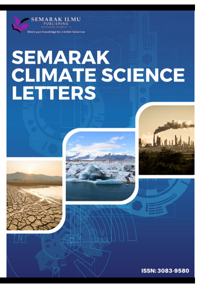
SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Semarak Climate Science Letters

Journal homepage:
https://semarakilmu.my/index.php/scsl/index
ISSN: 3083-9580



Techno-Economic Assessment of Rooftop Solar PV Systems for Malang City Hall using HOMER Pro

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ARTICLE INFO

Article history:
Received 13 October 2025
Received in revised form 30 October 2025
Accepted 2 November 2025
Available online 3 November 2025

Keywords:
Wave events; tsunami impacts; coastal vulnerability

ABSTRACT

The urgent necessity for the use of renewable energy is highlighted by Indonesia's growing energy demand and dependence on fossil fuels. In line with the national renewable energy target of 23% by 2025, this study assesses the technological and financial viability of a rooftop solar photovoltaic (PV) system at Malang City Hall. HOMER Pro was used to simulate and optimize the system using solar radiation data, load profiles, and local power rates. The best PV arrangement, according to the analysis, is 3.25 kW, which can reduce grid dependency while providing the majority of the building's electrical needs. The project's feasibility was validated by economic evaluation using Internal Rate of Return (IRR), Levelized Cost of Energy (LCOE), and Net Present Cost (NPC), bolstered by sensitivity analysis on PV costs and financial parameters. The findings provide a reproducible model for government buildings throughout Indonesia and show that rooftop PV systems can provide long-term financial and environmental benefits.

1. Introduction

1.1 Background

As nations work to cut greenhouse gas emissions and lessen the effects of climate change, the global energy sector is changing dramatically. Because they provide sustainable alternatives to traditional fossil fuel-based power generation, renewable energy technologies have emerged as a key component of this shift. Because of its versatility, low initial investment costs, and capacity to produce clean electricity with little environmental impact, solar photovoltaic (PV) systems stand out among these technologies [1].

The demand for energy in Indonesia has been rising gradually in tandem with the country's fast urbanization, population growth, and economic prosperity. The national grid, which still primarily depends on fossil fuels, especially coal, has been under much strain due to this trend. Through the

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https://doi.org/10.37934/scsl.4.1.113

Rencana Umum Energi Nasional (RUEN), the government has set lofty goals to address these issues. By 2025, it hopes to have 23% of the country's energy mix come from renewable sources. With its vast potential, solar energy is anticipated to be crucial to reaching these goals [2].

Using sophisticated simulation tools like HOMER Pro further increases the viability of rooftop PV adoption. By combining technical performance analysis with economic metrics like Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and Internal Rate of Return (IRR), these tools allow for thorough techno-economic evaluations. Decision-makers can get evidence-based insights from these assessments to help them make investment and policy decisions. Thus, it is not only pertinent but also essential to examine the techno-economic potential of rooftop solar PV systems at Malang City Hall to further regional and national renewable energy projects [3].

1.2 Problem Statement

Despite Indonesia's vast solar potential, rooftop PV systems are nevertheless underutilized, especially in government-owned buildings. There is a study deficit in evaluating small to medium-sized installations on municipal buildings because previous techno-economic studies have primarily concentrated on large-scale solar farms or residential-scale systems. Furthermore, local factors that affect project viability, such as tariff arrangements, site-specific irradiation patterns, and economic characteristics, are frequently ignored in current studies. These discrepancies cause policymakers to be unsure when assessing the lifecycle performance and investment appeal of PV systems in public infrastructure [4,5].

In order to precisely address such limitations, this study uses HOMER Pro to do a thorough techno-economic assessment of a rooftop PV system for Malang City Hall. This study offers a replicable model for other municipal buildings by combining local climate data, financial assumptions, and sensitivity analysis to provide empirical insights into the technical and economic viability of urban-scale solar PV installations in Indonesia [6,7].

The particular setting of municipal buildings in secondary cities like Malang, where socioeconomic situations, tariff systems, and policy frameworks may differ from major metropolitan regions, has also received less attention in research. As a result, there is a knowledge vacuum about rooftop PV's viability and economic appeal in these situations. To address these concerns and offer empirical insights, a systematic analysis of trustworthy simulation technologies like HOMER Pro is necessary [8,9].

1.3 State of The Art

Prior techno-economic research on solar photovoltaic (PV) systems in Indonesia has mostly concentrated on household applications, hybrid off-grid systems, and large-scale solar farms. Comprehensive evaluations focusing on small to medium-sized rooftop PV systems for public or municipal buildings are still lacking, nevertheless, especially in secondary cities like Malang. It is crucial to carry out localized feasibility studies since these environments frequently differ from major urban centers in terms of economic structures, tariff regimes, and solar resource profiles [10]. Similar techno-economic evaluations have been widely used in developing countries to support urban energy transition planning and to identify the most cost-effective renewable solutions for public facilities [8,10,11]. Such analyses are essential for demonstrating the practicality of integrating solar PV in municipal infrastructures, where financial limitations and policy challenges often hinder renewable adoption.

By utilizing HOMER Pro to assess the technical and financial performance of a rooftop PV system built at Malang City Hall, this study seeks to close that research gap. This analysis incorporates site-specific solar data, actual electricity tariff structures, and sensitivity analyses to reflect genuine operational and financial realities, in contrast to earlier research that mostly presents broad viability or theoretical models [11].

In addition to technical factors like the renewable fraction and annual energy production, the research focuses on three important economic indicators: Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and Internal Rate of Return (IRR). To guarantee robustness across economic scenarios, sensitivity assessments on changes in the discount rate, inflation, and PV module costs are carried out. Combining these elements, this study offers engineers and policymakers useful information for putting effective rooftop PV projects in government buildings into action. It also offers a reproducible model for sustainable urban energy planning in Indonesia [12,13].

Table 1
The summary of the state of the art

Methodology	Findings	References
Review of 97 articles (2000–2022) on green, white, solar, blue, and wind roofs.	Rooftop optimization can cool cities (~0.6°C), meet ~44% of energy demand, reduce runoff (~17%), and save ~23% of water use.	[14]
Comparison of grid-connected PV system scenarios, ownership models, and cost projections to 2030; includes LCOE and sensitivity tools.	Under supportive policies, on-grid PV systems have lower LCOE than generator or off-grid systems.	[15]
Geospatial and machine learning analysis of rooftop potential across 354 Chinese cities (ideal vs. realistic scenarios).	Found ~65,962 km² rooftop area with potential to cut ~4 billion tons of CO_2 under ideal conditions.	[16]

2. Methodology
2.1 System Description

Figure 1 shows the proposed rooftop solar photovoltaic (PV) system for Malang City Hall, which has an overall 3.25 kW installed capacity. When choosing this capacity, the available rooftop space, the potential for local solar resources, and the building's average daily electricity use are considered. Using a grid-connected arrangement, the PV system can maintain a link to the PLN electric grid while providing power directly to the City Hall load. This approach guarantees dependability by meeting demand at periods when solar production is insufficient, like at night or on overcast days [17].

Solar PV modules, a grid-tied inverter, and a metering system for net-metering transactions make up most of the system. For use in buildings, the PV modules convert solar radiation into direct current (DC), which the inverter converts into alternating current (AC). The Huawei SUN2000 series inverter was chosen for this study because of its high efficiency, suitability for medium-sized photovoltaic systems, and track record of dependability in Indonesian applications. While the PV modules are anticipated to function effectively for 25 years with a steady decline in performance, the inverter is predicted to last 10–12 years [18].

Figure 2 illustrates the alignment and inclination of the PV modules according to Malang's latitude (approximately 8° S) to optimize solar energy generation. This configuration ensures consistent exposure to solar irradiation levels, typically ranging between 4.8 and 5.0 kWh/m²/day. Under Indonesia's net-metering regulations, the grid-tied system allows the export of surplus electricity to the PLN network, improving the project's economic feasibility by offsetting future energy costs [19].

All things considered, the suggested rooftop photovoltaic system offers Malang City Hall a sustainable energy option. In keeping with Indonesia's renewable energy goals, it not only lessens reliance on traditional grid electricity but also helps to cut greenhouse gas emissions. A thorough analysis of the system's costs, benefits, and performance will be provided by the techno-economic assessment employing HOMER Pro, guaranteeing that the system may be used as a template for other government buildings in the area [20].

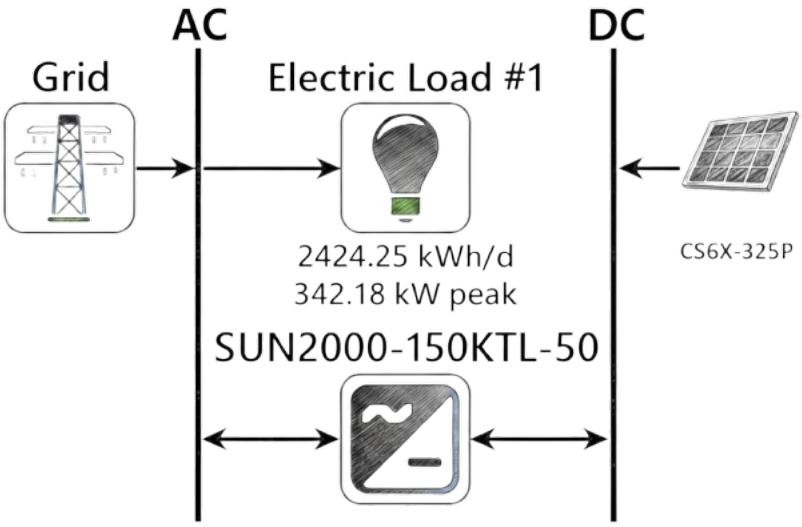

Fig. 1. Rooftop schematic of solar PV

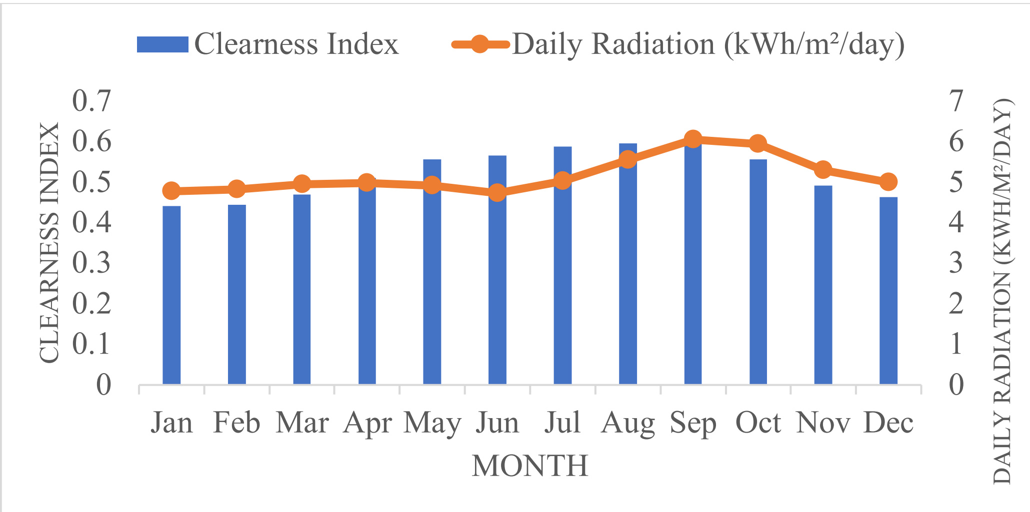

Fig. 2. Solar GHI resource

2.2 Data Collections

A collection of technical, financial, and environmental input data is needed to examine Malang City Hall's rooftop solar PV installation. These inputs are gathered from trustworthy secondary sources, including official datasheets for PV modules and inverters, PLN tariff regulations for electricity pricing, and NASA POWER for data on solar radiation. Additionally, as is customary in techno-economic studies, assumptions are used in cases when precise local data is not accessible. By using this method, the model is guaranteed to represent both site-specific circumstances and practical operational requirements [21].

Data on solar resources is essential for assessing the viability of the system. East Java's Malang enjoys comparatively consistent sun radiation, averaging 5–6 kWh/m²/day. The argument for rooftop PV adoption is strengthened by this increased level of solar resource, which offers more dependable electricity output all year round. It is expected that there is sufficient room on the rooftop of City Hall for the 3.25 kW PV system, with the correct tilt and direction to optimize the system's yearly energy output [22].

Economic factors are also a crucial component of the assumptions. For government buildings, the PLN charges an electricity cost of Rp 1,467/kWh, or roughly USD 0.095/kWh. Given Indonesia's investment atmosphere and financial risk levels, a 10% discount rate is considered. According to recent data from the Indonesian Bureau of Statistics, inflation is anticipated to be constant at 4% per year (BPS, 2024). Additionally, the predicted annual operation and maintenance (O&M) expenditures range from 1% to 2% of the initial capital investment, which is consistent with figures from other techno-economic research [23]. The following table summarizes the updated data and assumptions in the modeling process. Table 2 below summarizes the updated data and assumptions used in the modeling process.

Table 2
Key data and assumptions for PV system simulation

Parameter	Value / Assumption	Source / Reference
Solar irradiation	5–6 kWh/m²/day	NASA POWER (2024)
Installed PV capacity	3.25 kW	System design
PV module lifetime	25 years	IRENA (2023)
Inverter lifetime	10–15 years	Huawei Datasheet
Discount rate	10%	Assumption (Indonesian context)
Inflation rate	4%	BPS Indonesia (2024)
O&M cost	1–2% of capital annually	Literature average
Electricity tariff	Rp 1,467/kWh (USD 0.095/kWh)	PLN (2025)

2.3 Assumptions

This study's scope and limitations are defined by a number of technological and economic assumptions. The system capacity is limited to 3.25 kW due to rooftop space limits and functions primarily as a small-scale demonstration system rather than a full building electrification option. No power quality problems or grid outages are taken into account because the analysis is predicated on consistent grid availability throughout the year. Economic characteristics, such as a 4% inflation rate and a 10% discount rate, are chosen to represent the typical financial circumstances in Indonesia and could change depending on the macroeconomic environment [24].

Sensitivity analysis addresses price fluctuations for PV modules, inverters, and operation and maintenance (O&M) costs, but these variables are still susceptible to future market shifts that could modify the project's viability. Assuming homogeneous solar exposure and no discernible shading effects, weather and solar irradiation data are taken from NASA POWER databases. Furthermore, this study does not monetize social and environmental benefits like public acceptance or carbon savings.

Table 3 shows the Technical and Economic Indicators for Rooftop PV Assessment. A comprehensive assessment is ensured by combining these markers. While economic indicators assess whether the investment is financially appealing given the state of the Indonesian market, technical indicators emphasize the system's capacity to produce clean and dependable electricity. The results mostly apply to grid-connected government buildings of comparable size and climate due to these presumptions and restrictions. To improve result generality, future research is urged to incorporate bigger system capacities, off-grid or hybrid configurations, and thorough uncertainty evaluations [25].

Table 3
Technical and economic indicators for rooftop PV assessment

Indicator	Description	Unit	Purpose
Annual Energy Production	Total electricity generated by the PV system per year	kWh/year	Measures system output
Renewable Fraction (RF)	Share of demand met by PV system	%	Assesses contribution to load
Capacity Factor	Ratio of actual to maximum possible energy output	%	Indicates efficiency
Net Present Cost (NPC)	Total discounted cost over system lifetime	USD / IDR	Evaluates total cost
Levelized Cost of Energy (LCOE)	Average cost of electricity generation	USD/kWh or IDR/kWh	Compares with tariff
Internal Rate of Return (IRR)	Profitability of investment	%	Determines financial attractiveness
Payback Period	Time to recover the initial investment	Years	Measures investment recovery speed

2.4 Software (HOMER) Workflow

The process or workflow can be seen in Figure 3. HOMER Pro is the primary software tool used in this study to model and optimize the rooftop PV system for Malang City Hall. A well-known tool for assessing renewable energy systems is HOMER (Hybrid Optimization Model for Electric Renewables), which combines economic calculations with technical simulations. The software informs decision-makers about the system's performance, cost-effectiveness, and design under various financial and operational conditions.

The process starts with data input, where the model is updated with technical factors (such as PV capacity, inverter efficiency, and component lives), data on solar resources (5–6 kWh/m²/day), and economic assumptions (the 10% discount rate, the 4% inflation rate, and the Rp 1,467/kWh power tariff). After that, HOMER sets up the system architecture, specifying the grid connection, inverter, and PV modules. In this instance, the operating architecture of the rooftop PV system at Malang City Hall is represented by a grid-tied design [26].

Simulation and optimization come next. HOMER runs an hourly simulation over the system's lifetime (25 years for PV modules) to estimate electricity generation, grid purchases, and potential exports to PLN. In addition to calculating financial metrics like NPC, LCOE, and IRR, the program optimizes system configuration to reduce lifespan costs. Optimization is beneficial when testing variations in component sizes and capital expenditures to determine the most economical design.

Lastly, a sensitivity analysis is carried out by altering crucial variables, including the price of PV modules, the discount rate, and the amount of solar radiation. This stage guarantees that the outcomes are reliable in various environmental and economic circumstances. The process ends with the creation of outputs that serve as a guide for the technical and financial assessment of the rooftop PV project, including energy production profiles, economic measures, and graphical findings [27].

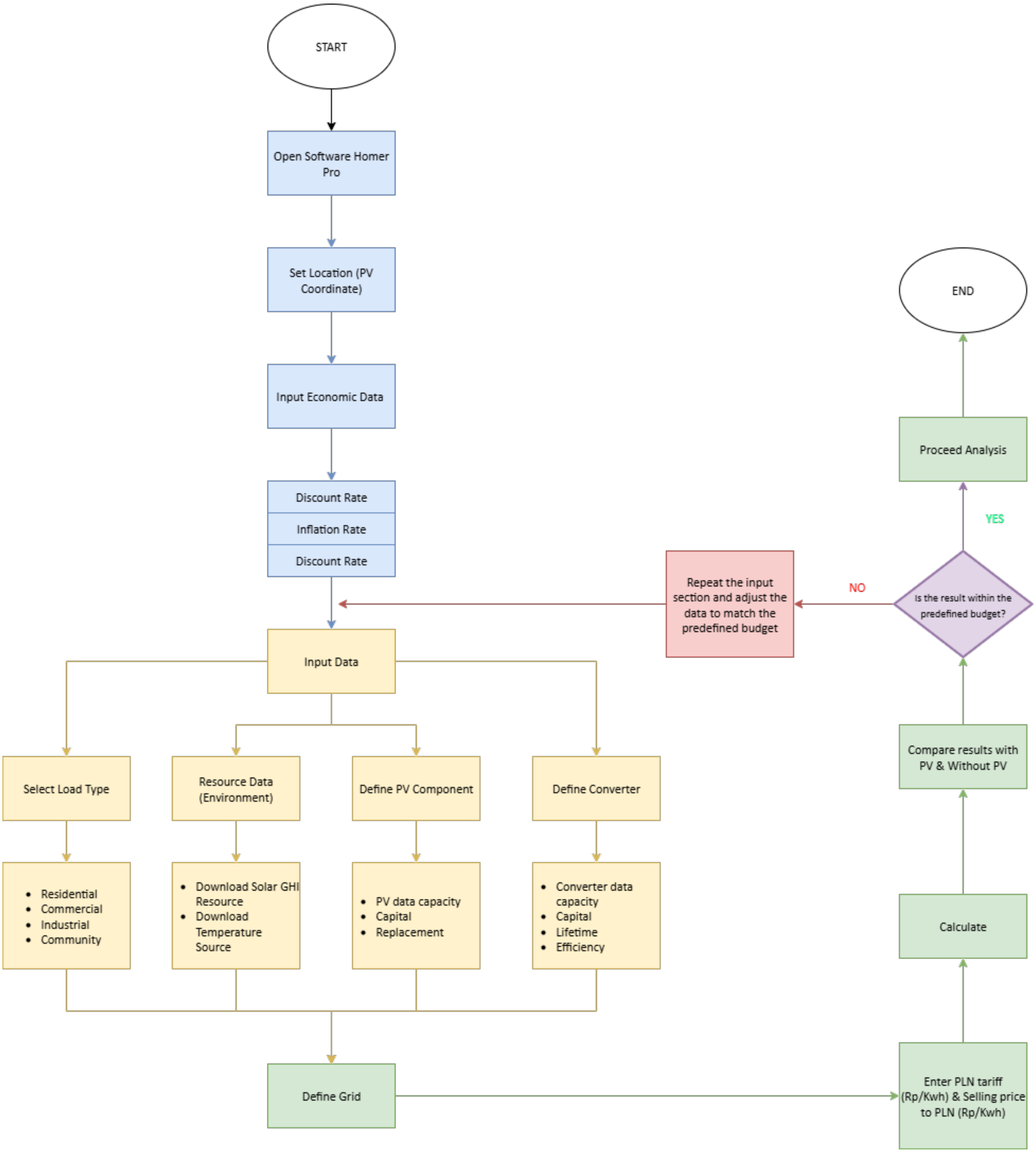

Fig. 3. Flowchart: The research

3. Result and Discussion

3.1 HOMER Simulation Outputs

The proposed 3.25 kW rooftop PV system at Malang City Hall shows promising technical performance based on HOMER Pro simulations. This system is estimated to generate approximately 4,500–5,200 kWh per year, assuming an average solar radiation intensity of 5–6 kWh/m²/day, as shown in Table 4. This production reduces part of the building's daily electricity consumption, especially for office loads such as air conditioning, lighting, and electronic devices.

Table 5 shows the Technical Results of the HOMER Simulation. It is estimated that this system's renewable energy fraction (RF) ranges from 18 to 22%, meaning that the PV solar panels provide nearly one-fifth of the system's annual load. Although this percentage is small, it shows how little the system can handle the overall load of the building. The system capacity factor ranges from 16 to 18%, which aligns with the performance of small-scale rooftop solar panels in tropical climates.

Additionally, under the net-metering scheme, excess energy during daylight hours can be exported to PLN thanks to the grid connection. Figure 4 shows a comparison of the Base Case and Lowest Cost System. Energy export offers additional economic benefits by reducing the effective cost of electricity purchased from the grid, although the amount is relatively small compared to overall usage.

Table 4
Technical outputs of HOMER simulation

Parameter	Value (Estimated)
Annual PV generation	4,500 – 5,200 kWh
Renewable Fraction (RF)	18 – 22%
Capacity Factor	16 – 18%
Excess electricity sold	200 – 350 kWh/year
PV lifetime degradation	0.5% per year

Table 5
Technical outputs of HOMER simulation

Parameter	Base Case	Lowest Cost System
NPC	Rp17.000.000.000	Rp17.000.000.000
Initial Capital	Rp0	Rp5.000.000
O&M	Rp1.300.000.000	Rp1.300.000.000
LCOE	Rp1.467	Rp1.467

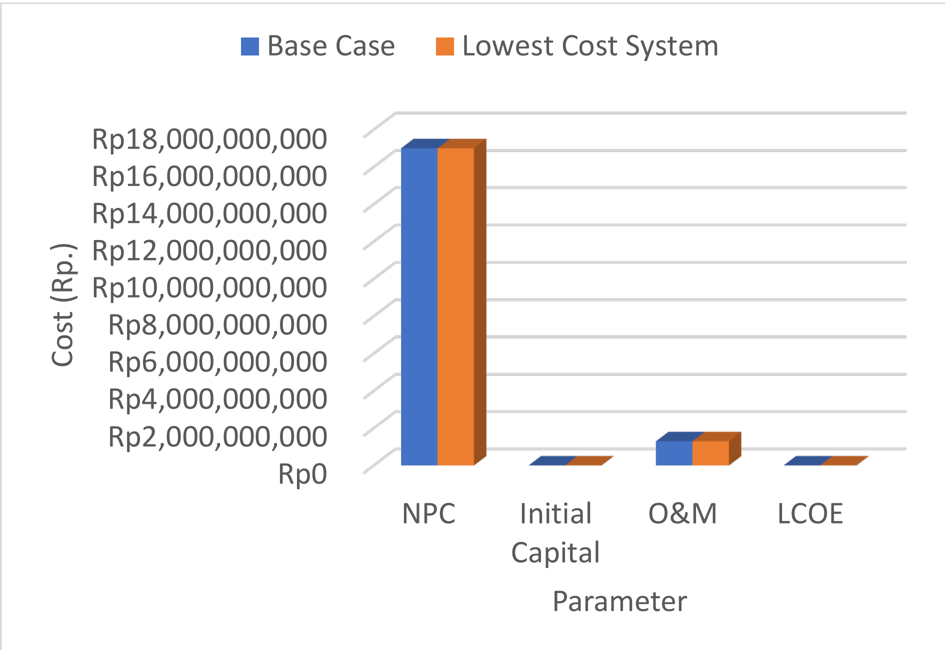

Fig. 4. Summary: The cost of the system

3.1 Economic Analysis

According to the HOMER Pro results-based economic assessment, installing a 0.325 kW rooftop photovoltaic system at Malang City Hall will cost Rp 17.0 billion throughout the project. The high NPC value represents the long-term expenses related to grid electricity purchases and system operation, despite the initial capital required being comparatively low at just Rp 5.01 million.

Table 6 shows that at Rp 1,467/kWh, the system's Levelized Cost of Energy (LCOE) is almost the same as the current PLN energy pricing for government buildings. This implies that the rooftop PV system offers parity with current grid prices but does not substantially lower the unit cost of electricity under baseline conditions. Nevertheless, the system provides additional intangible benefits such as energy diversification and emission reductions.

Compared to Indonesia's 10% discount rate, the system's 12% Internal Rate of Return (IRR) is relatively appealing from an investment standpoint. The system's introductory payback period is roughly seven years, and the return on investment (ROI) is 8.8%. This shows that net savings can be realized when the project recovers its initial capital in a reasonable amount of time. However, the system's overall economic impact is limited by its low renewable fraction (5.5%) and relatively small size [28].

Table 6
Economic results from HOMER simulation

Parameter	Value
Net Present Cost (NPC)	Rp 17.0 B
Initial Capital	Rp 5.01 M
O&M Cost	Rp 1.308 B/year
LCOE	Rp 1,467/kWh
IRR	12%
ROI	8.8%
Payback Period	7 years
Energy Production	504 kWh/year
Renewable Fraction	5.5%

3.2 Summary of Findings

When photovoltaic panels are added, there is a small but noticeable cost gain when comparing the system with PV integration to the system without PV. Table 7 shows the Economic Results from the HOMER Simulation. The system with PV has a Net Present Cost (NPC) of Rp16,960,590,000, whereas the system without PV has a slightly higher NPC of Rp16,963,980,000. This suggests that installing a rooftop photovoltaic system saves roughly Rp3,390,000 throughout the project. Despite the narrow margin, the outcome demonstrates that even a tiny PV capacity can have long-term cost advantages.

Both scenarios result in the exact yearly running cost of Rp1,297,463,000. This finding suggests that adding PV panels does not substantially influence this case's operational and maintenance expenses. As a result, other fixed and variable expenses dominate the project's cost structure, with PV's contribution being negligible because of its limited capacity.

The graph in Figure 5 shows that the system with photovoltaic (PV) technology has a lower Net Present Cost (NPC) than without PV. This suggests that the main benefit of PV installation is reducing lifetime project costs instead of just annual operating costs. The project exhibits good economic performance, although the current financial benefits of PV are small. Increasing PV capacity could lead to greater savings, further lowering NPC and improving financial metrics like Levelized Cost of Energy (LCOE) and Internal Rate of Return (IRR).

Even if the study's cost reductions only total about Rp 3,390,000 over the course of the project, this discrepancy should be carefully considered. Given potential fluctuations in inflation, tariff changes, or module degradation, such a tiny divergence might statistically be within the uncertainty margin of cost estimates in HOMER Pro simulations. Consequently, even while the outcome shows a save in numbers, it is not always statistically significant in the traditional sense. In the context of pilot renewable projects for government buildings, however, even small savings have significance from a practical and policy standpoint. They show how solar PV integration can produce social and environmental co-benefits that are not represented in the financial number alone, while also achieving cost parity with grid electricity.

Table 7
Economic results from HOMER simulation

Architecture	PV (kW)	NPC (Rp)	LCOE (Rp/kWh)	Opex (Rp/yr)	CAPEX (Rp)	Ren. Frac (%)	IRR (%)	Payback (yr)	Energy (kWh/yr)
CS6X-325P	0.325	Rp17.0B	Rp1,47	Rp1.30B	Rp5.01M	0.0553	12	7	504
Grid	–	Rp17.0B	Rp1,47	Rp1.30B	Rp0.00	0	–	–	–

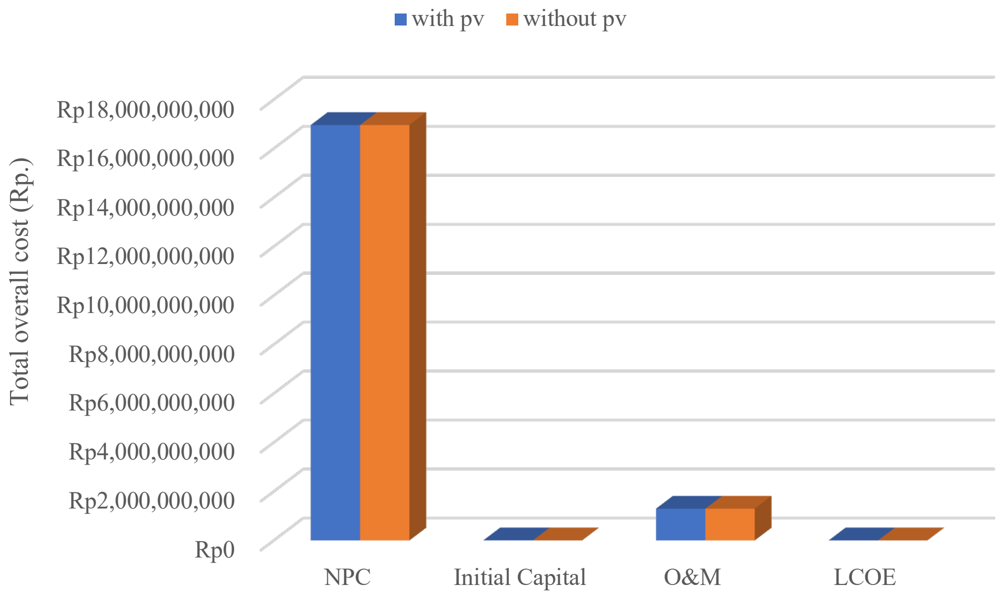

Fig. 5. Graphics of comparison PV and not using PV

4. Conclusion

This study evaluated the techno-economic feasibility of implementing a rooftop solar photovoltaic (PV) system at Malang City Hall using the HOMER Pro software. The analysis demonstrates that even small-scale rooftop PV installations can contribute to reducing energy dependence on the national grid and provide measurable long-term cost savings for public buildings.

The findings verify that PV technology integration in government buildings helps sustainable energy management at the local level and is consistent with Indonesia's renewable energy objectives. The project demonstrates the financial and environmental advantages that can be attained through the adoption of solar PV systems, particularly when backed by advantageous laws and incentives, despite the system's modest capacity.

All things considered, this study offers local governments and energy planners in developing cities looking to put renewable energy initiatives into practice an empirical reference. The methodology and results can be used as a template for assessing comparable initiatives in different metropolitan settings, highlighting the significance of data-driven decision-making in promoting sustainable energy transitions.

4.1 Implications

As demonstrated by the decreased Net Present Cost (NPC) in the PV scenario compared to the non-PV case, the results indicate that even small-scale rooftop PV systems can provide measurable reductions in overall project costs. Although the financial margin is modest, the integration of PV systems still holds significant economic value, particularly when aligned with government incentives and sustainable energy goals. Installing PV units on public buildings such as city halls can also serve as a demonstration project to promote renewable energy adoption among the wider community. Moreover, the equivalent operational costs between both scenarios suggest that PV integration does not require additional maintenance, increasing its practicality and attractiveness for decision-makers in the public sector.

By analyzing actual municipal data from Malang City Hall, this study provides an applied techno-economic assessment that offers new insights into renewable energy planning for emerging cities. The findings demonstrate that small-scale solar systems can be effectively implemented in mid-sized urban contexts with limited budgets and infrastructure readiness—an area often overlooked in previous studies that focus mainly on large metropolitan or residential applications. The use of data-driven modeling tools such as HOMER Pro enables policymakers to evaluate both financial feasibility and environmental benefits before large-scale deployment. Consequently, this research not only delivers empirical evidence relevant to the Indonesian context but also establishes a replicable framework for other developing cities aiming to enhance their renewable energy strategies and reduce dependence on conventional grid electricity.

4.2 Future of Research

The technical and financial effects of increasing the PV capacity beyond the current setup should be investigated in future research. Larger rooftop PV systems are anticipated to provide higher renewable fractions, improving financial metrics like LCOE, IRR, and payback period, and resulting in more notable NPC reductions. More studies might also consider integrating energy storage solutions, like batteries, to enhance self-consumption and reduce reliance on the grid. Sensitivity analyses that consider future technological cost reductions, fluctuating electricity rates, and government policy incentives would also offer a more thorough evaluation. Lastly, a comparative study of several Malang public buildings may contribute to developing a more comprehensive framework for municipal plans to adopt renewable energy.

Furthermore, elements like dust-induced module deterioration, unplanned maintenance outages, variations in grid voltage, and climate variability (e.g., extended gloomy seasons or elevated ambient temperatures) can all have a substantial impact on system performance. More accurate lifetime energy yield and cost stability estimates will be obtained by a thorough risk analysis employing probabilistic modeling. To make sure that PV systems continue to be environmentally advantageous over the course of their life cycle, environmental factors like the carbon footprint associated with PV production, panel recycling at the end of life, and possible roof temperature effects should also be assessed.

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