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Original Article

Techno-Economic Analysis of On-Grid Solar Power Plants for Tulungagung Hydropower Operational Cost Savings Based on Production and Load Data

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ABSTRACT

The increasing energy demand and environmental challenges have accelerated the global shift toward renewable energy, with Indonesia possessing a substantial solar potential of 3,294 GW. This study investigates the techno-economic feasibility of a 40.9 kWp On-Grid Solar Power Plant as a supplementary energy source to reduce operational costs at the Tulungagung hydropower plant. A techno-economic analysis was conducted using 2024 solar PV production data from the ShinePhone application and the Tulungagung Hydropower business daily report, complemented by simulations from the Hybrid Optimization Model for Multiple Energy Resources (HOMER) to identify optimal system configurations. The actual solar power plant generated 52,499.9 kWh/year, contributing 15.66% of the plant's operational load of 335,150.71 kWh and resulting in annual cost savings of IDR 58,523,260, based on a PLN tariff of IDR 1,114.74/kWh. In comparison, HOMER simulations projected a higher generation of 74,265 kWh/year, with a net present cost (NPC) of IDR 6,461,879,000 and a cost of energy (COE) of IDR 1,142.36. While the PLTS has proven technically and economically viable as a complementary energy source, its current capacity remains insufficient to fully meet the hydropower plant's operational load, indicating the need for further system optimization and potential integration of energy storage solutions.

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1. Introduction

The global energy crisis, climate change, and rising carbon emissions have accelerated the shift towards clean and sustainable energy sources worldwide [1]. Fossil fuel dependence, especially on coal and petroleum, not only damages the environment but also threatens long-term energy security. Renewable energy, particularly solar power, offers a crucial solution owing to its abundance and low environmental impact [2]. Indonesia, as a tropical country, has vast solar energy potential estimated at approximately 3,294 GW; however, less than 1% of this potential was utilized in 2023 [3].

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East Java, one of Indonesia's provinces with significant electricity demand, has experienced an annual industrial electricity growth rate of around 4% [4]. This underscores the importance of adopting renewable energy technologies, such as solar power plants, to supplement the energy supply in the region. According to data from the Directorate General of New, Renewable Energy, and Energy Conservation, processed by the National Energy Council's Secretary General, East Java Province holds a solar potential of 176.4 GW, with areas such as Tulungagung receiving consistent solar radiation throughout the year. This aligns with the United Nations Sustainable Development Goal 7, which promotes clean energy access to reduce fossil fuel dependence and lower carbon emissions [5].

The Tulungagung hydropower plant, located in Tulungagung Regency, East Java, primarily generates electricity using hydropower to meet local demand and support the regional grid. In accordance with national policies promoting clean and environmentally friendly energy, the plant has begun integrating an on-grid solar power plant system installed on its rooftop as an additional energy source for the plant.

A solar power plant converts sunlight into electrical energy using photovoltaic (PV) panels. On-grid solar power plant systems are directly connected to the main power grid (PLN), enabling the generated electricity to be used immediately or fed back into the grid [6, 7]. One key advantage of on-grid solar power plants is that they do not require energy storage batteries, which simplifies installation and reduces costs [8]. The generated energy can reduce reliance on fossil fuel-based electricity and enhance energy sustainability [9, 10].

The on-grid solar power system at the Tulungagung hydropower plant has a total installed capacity of 40.9 kWp and supplies electricity to internal loads during daylight hours. When hydropower generation is unavailable, the solar PV system reduces the plant's electricity consumption from PLN, thereby improving the overall energy efficiency and lowering the operational costs. Although PLN electricity costs may appear modest on a daily basis, the annual savings can amount to millions of rupiah, depending on load profiles and system performance. Additionally, the absence of batteries in the system reduces the initial investment and maintenance costs.

Previous studies have examined solar power efficiency across residential, industrial, and commercial applications, as listed in Table 1. However, none have specifically focused on the role of solar power as a backup energy source for hydropower plants with substantial operational loads, particularly during the downtime of generators. This research gap highlights the novelty and relevance of this study.

Table 1. Summary of previous studies on solar power applications.

Authors	Study focus	Key findings
Gifson et al. [11]	Design and build on-grid solar power plants in Ecopark.	Contribution 60% load, performance ratio (PR) 85%
Aji et al. [12]	Performance of on-grid solar power plants at BPR Wanayasa .	Export 30-40%, import 80-85%, save 22.1%
Laksono et al. [13]	Solar power plant for Shashi's baby porridge business.	10% reduction in electricity dependence
Rega et al. [14]	Rooftop solar power plant at Pagilaran tea factory.	Meets 95.85% load, PR 77.5%
Denis et al. [15]	Solar PV for seaweed drying.	Efficiency ±100% when optimal
Prayogi et al. [16]	Solar power plant for PagiFarm hydroponic garden.	40% reduction in operational costs
Adi et al. [17]	40 kWp rooftop solar power plant at the Bali regional office.	Electricity cost savings of 41.58%
Sreenath et al. [18]	Solar PV design and analysis at Kuantan airport, Malaysia, with glare considerations.	20 MW solar power plants produce 26,304 MWh/year, PR 76.88%, CUF 15.22%, effective except for Zone 8 (glare)
Gunoto & Hutapea [19]	Analysis of solar panel power at 30 kVA rooftop on-grid Solar Power Plant in the PT. ELB for efficiency and cost	Efficiency drops from 17% to 15.4% due to the temperature of 53°C, but the capacity of 30 kW is achieved thanks to

Authors	Study focus	Key findings
	savings.	the high irradiance (1300 W/m²)
Febriana Pratiwi et al. [20]	Design of 163.8 kWp On-Grid rooftop solar power plant for the power supply of the textile industry.	Energy production of 252.48 MWh/year (manual) and 248.8 MWh/year (PVsyst), NPV of IDR 2.14 billion, payback of 8 years
Octavia et al. [21]	A study of the potential of rooftop solar power plants in Makassar to increase renewable energy and reduce carbon emissions in households.	PLN's power savings 39.9%-110.5%, carbon emissions down 96.7% (3.3% from PLN), panel efficiency 20.3%
Mubarok et al. [22]	Analysis of the impact of climate change on the efficiency of FTI UII solar power plant (10 kWp) in campus buildings.	Highest efficiency 64-65% (2019), lowest 29% (2018) due to maintenance and climate, production of 33,358 kWh (5.5 years)
Burhandono et al. [23]	Planning of Rooftop On-Grid Solar Power Plants for the Amurang PLTU office building to reduce auxiliary power and increase NPHR.	1.8 kWp solar power plant (6 panels 300 Wp), saving 133 kWh/month, NPHR down 20.15 kCal/kWh/month, cost IDR 71.5 million
Dewi et al. [24]	Comparison of energy output from 1 kWp On-Grid Rooftop Solar Power Plant with 1300 VA household energy needs in Cilacap.	1 kWp solar power plant (PLTS) generates 42% of the annual energy needs (9.3 kWh/day), saving 42% of electricity from the grid (PLN), with an average solar radiation of 3.6 kWh/m²/day.
Nazar et al. [25]	Study of the performance of 10 kWp On-Grid rooftop solar power plants in Dayah Ulee Titi for operational cost savings.	The 10 kWp on-grid rooftop solar power plant at Dayah Ulee Titi has an average power capacity of 81.3% (8,130 W), a peak power output of 97.1% (9,714.5 W), operational cost savings of 20% over 5 months, and a PLN energy import rate of 53.1% during holidays.

This study addresses the identified research gap by investigating the role and cost-saving potential of on-grid solar power plants at the Tulungagung hydropower plant in Indonesia. It leverages real-world data obtained from the ShinePhone application, business daily reports, and simulations conducted using the HOMER software under the specific condition that the hydropower generator is offline. This methodology offers new insights into the integration of on-grid solar power plants into hydropower systems. Accordingly, this study aims to perform a comprehensive techno-economic analysis of deploying on-grid solar power as a backup energy source to support the operational loads of the Tulungagung hydropower plant. The analysis covers both technical and economic dimensions, including energy production capacity, load profiles, cost efficiency, and financial viability. Furthermore, this study aims to assess the broader potential of on-grid solar power development in Tulungagung and contribute to the transition toward clean and sustainable energy solutions.

2. Methods

2.1. *Materials and tools*

This study utilized production data from the installed solar PV system and operational cost records of the Tulungagung hydropower plant in 2024. The primary data sources included the ShinePhone application (which monitors the performance of the on-grid accounting for the solar power plant), simulation results from the HOMER software, and the official Daily Business constituting the Business Report of the Tulungagung hydropower plant.

The solar PV system installed at the facility is an on-grid solar power system configuration without energy storage, which means that all the generated electricity is directly consumed in real time. This system is designed to supply power for up to 12 h of operation per day, thereby reducing electricity expenses from the national utility grid (PLN) during periods when the hydropower generator is nonoperational.

Figure 1 illustrates the energy flow in the on-grid solar power system at the Tulungagung hydropower plant. The system consists of a 40.9 kWp solar panel array with mixed module capacities (330, 450, and 580 Wp) that generates DC electricity. This DC power was then converted to AC power using a 40-kW inverter and used to support a partial daily operational load of 915.13 kWh.

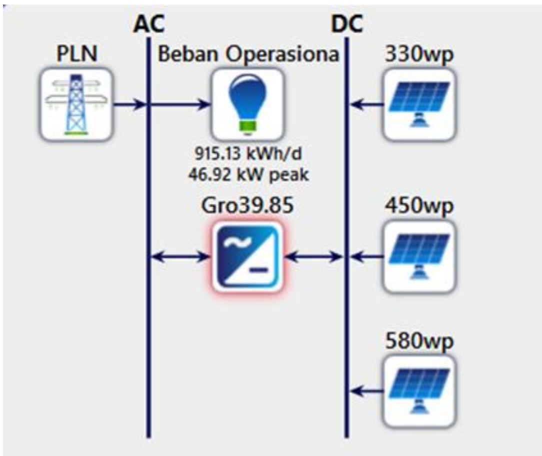

Figure 1. Tulungagung hydropower on-grid solar power plant scheme.

2.2. *Study design and data analysis*

This study conducted a techno-economic analysis using a quantitative approach based on production and operational expenditure data. The analysis was conducted in structured phases, including data collection and processing during the internship period from January to May 2025. Data related to the on-grid solar power plant's energy production and the operational load of the Tulungagung Hydropower plant were obtained through the ShinePhone application, which is integrated with the solar system, and from the Tulungagung Hydropower business's daily report. The location of the Tulungagung hydropower plant is illustrated in Figure 2.

Quantitative data processing was performed manually to determine the average daily production, contribution of solar power to operational expenses, and resulting cost savings, calculated using PLN's electricity tariff of IDR 1,114.74/kWh. Further technical optimization was conducted using the HOMER software to simulate and refine the configuration of the on-grid solar power plant. The accuracy of the simulation results was validated by comparing the predicted solar power output with the actual performance data obtained during the internship, which ensured the reliability of the model under real-world operating conditions.

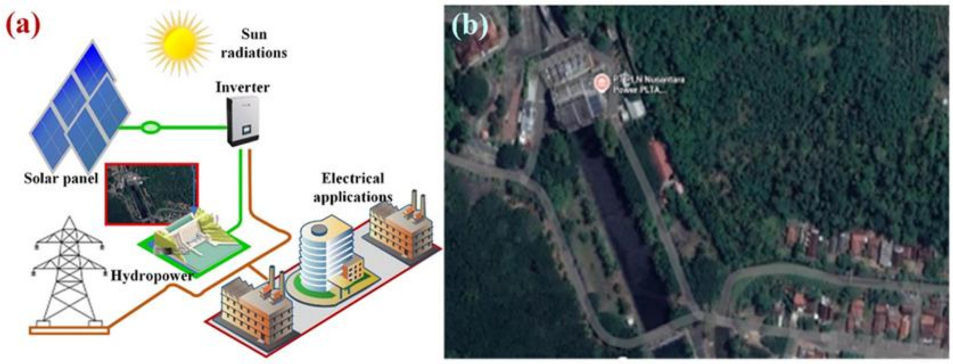

Figure 2. Integration of hydropower and solar power plant systems: (a) schematic diagram of the integrated energy system; (b) aerial view of the hydropower site in Tulungagung Regency.

The Tulungagung hydropower plant is situated in a region with favorable solar energy potential, characterized by an average annual daily solar radiation of 5.366 kWh/m²/day. Additionally, the area exhibits an average Clearness Index of 0.551, suggesting generally clear sky conditions throughout the year, despite increased cloud cover during the rainy season (Table 2).

Table 2. Solar radiation and clearness index data at the Tulungagung hydropower plant.

Month	Clearness index	Daily radiation (kWh/m^2/day)
Jan	0.448	4.850
Feb	0.456	4.940
Mar	0.503	5.280
Apr	0.549	5.330
May	0.596	5.260
Jun	0.583	4.860
Jul	0.612	5.220
Aug	0.618	5.720
Sep	0.613	6.220
Oct	0.569	6.070
Nov	0.502	5.420
Dec	0.487	5.250

2.3. *Main components of the on-grid solar power system at the Tulungagung hydropower plant*

The On-Grid Solar Power System at the Tulungagung hydropower plant primarily comprises two main components: solar panels and inverters. Solar panels act as photovoltaic (PV) converters, transforming solar radiation into direct current (DC) electricity [26]. The installed capacity was 40.9 kWp, using panels with power ratings of 330, 450, and 580 Wp. In the HOMER simulation, the panel configuration was based on the maximum rated capacity of the installed modules. These panels are optimally oriented to maximize daily solar energy capture and significantly contribute to the operational load of the plant during the generator downtime. The technical specifications, including efficiency, voltage, and current, are listed in Table 3.

Table 3. Specifications of the solar power system components at the Tulungagung hydropower plant.

Components	Qty	Parameter	Value
Canadian Solar CS6U-330P	45	Maximum Power (Pmax)	330 Wp
		Optimum Voltage (Vmp)	37.2 V
		Optimum Current (Imp)	8.88 A
		Open Circuit Voltage (Voc)	45.6 V
		Short Circuit Current (Isc)	9.45 A
Trina Solar TSM-450DE17M(II)	36	Maximum Power (Pmax)	450 Wp
		Optimum Voltage (Vmp)	41 V
		Optimum Current (Imp)	10.98 A
		Open Circuit Voltage (Voc)	49.6 V
		Short Circuit Current (Isc)	11.53 A
Jinko Solar JKM580N-72HL4-V	17	Maximum Power (Pmax)	580 Wp
		Optimum Voltage (Vmp)	42.37 V
		Optimum Current (Imp)	13.69 A
		Open Circuit Voltage (Voc)	51.02 V
		Short Circuit Current (Isc)	14.47 A
Growatt Inverter 40 kW	45	Output Power	40 kW
		Output Frequency	50-60 Hz
		Input Voltage	48 V
		Efficiency	99 %

Inverters convert the DC electricity generated by solar panels into alternating current (AC), which is compatible with standard industrial and commercial electrical systems [27]. The facility uses a 40-kW inverter to reliably integrate solar power into a grid-connected system. This inverter supports stable and efficient energy delivery, particularly during peak solar production when the hydropower generator is not operational. The combination of high-capacity PV modules and a robust inverter enables the plant to offset a substantial share of its energy demand, thereby reducing its reliance on the national grid (PLN) and achieving notable cost savings in the long term. The inverter specifications are presented in Table 3.

2.4. *Net present cost (NPC) and cost of energy (COE) analysis based on HOMER simulation*

The economic analysis included NPC, COE, and simulations performed using HOMER software. NPC represents the total system cost over its lifetime, incorporating component capital costs, replacement costs, maintenance expenses, fuel costs, and the salvage value of components at the end of the project life, adjusted by the annual discount rate. NPC accounts for both the initial investment and the ongoing operational costs. This can be calculated using the following equation [28]:

$$\mathrm{NPC} = \frac{C_{ann,tot}}{CRF,\ i.R_{proj}} \quad (1)$$

where $C_{ann,tot}$ is the total annualized cost (IDR/year), CRF is the capital recovery factor, i is the annual interest rate (annual), and R_{proj} is the project lifetime (in years).

The cost of energy (COE) represents the average cost per kilowatt-hour of electricity generated by a system over its operational lifetime. This was calculated by dividing the total annualized cost of the system by the total energy output, per year. The COE provides a standardized metric for evaluating the economic feasibility of systems. The COE is calculated using the following equation [29]:

$$\mathrm{COE} = \frac{C_{ann,tot}}{E_{tot\ serve}} \quad (2)$$

Where E_{tot} represents the total energy produced by the system. HOMER software was used to simulate and optimize the design of electrical power systems by providing technical and economic analyses, enabling users to evaluate the most cost-effective configurations and estimate the associated project costs over time.

HOMER is a simulation software widely used for the design and analysis of power generation systems. This enables a comprehensive technical and economic evaluation by simulating various system configurations under different operating conditions [30]. Using HOMER, users can identify the most cost-effective system design and obtain detailed estimates of both capital and operational expenditures over the project lifetime.

3. Result and Discussions

3.1. *On-grid solar power plant production at Tulungagung hydropower plant*

The total production of the on-grid solar power plant at the Tulungagung hydropower plant in 2024 was 52,499.9 kWh, as illustrated in Figure 3. These data reflect the actual energy output of the on-grid system, which operates without battery storage and directly supplies electricity to operational loads. Based on 365 days of observation, the average daily production was calculated as 143.8 kWh/day, as shown in Eq. (3). The generation performance highlights the capability of the system to provide a stable and measurable amount of electricity under typical operating conditions.

$$\text{Daily average} = \frac{52{,}499.9}{365} = 143.8\ \text{kWh/day} \quad (3)$$

Monthly data revealed fluctuations in energy production, with the highest output recorded in April (5,324.2 kWh) and the lowest in December (3,217.1 kWh). These variations are influenced by seasonal changes in solar irradiance, weather patterns and panel orientation. Despite these fluctuations, the on-grid solar power plant consistently provides a valuable energy supply to support operational demands, particularly when the hydropower generator is functioning. These production data serve as a critical baseline for evaluating the technical performance and economic feasibility of integrating solar energy into hydropower systems.

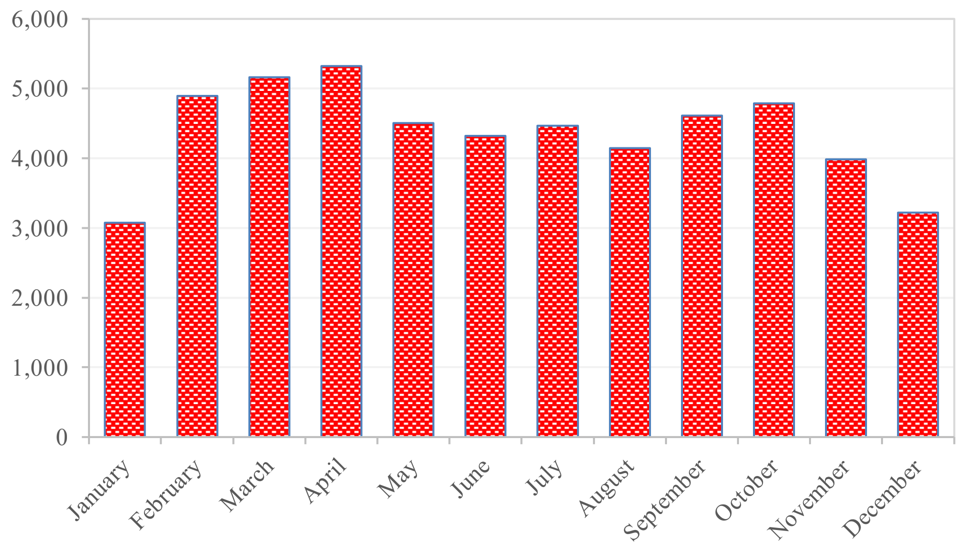

Figure 3. Solar power production data for the on-grid year 2024.

3.2. *Operational Burden of Tulungagung hydropower plant*

Figure 4 shows the operational load graph of the Tulungagung hydropower plant in 2024. During this period, the total operational load reached 335,150.71 kWh, with an average daily output of 915.71 kWh. If the hydropower generator is offline or not operating, the contribution of the on-grid solar power plant to the load can be calculated using the following equation:

$$\text{Solar power contribution (\%)} = \frac{\textit{Solar power plant production}}{\textit{Daily load}} \text{ x } 100\% \tag{4}$$

$$\text{PV-plant Contribution} = \frac{52499{,}9}{335150{,}71} \text{ x } 100\% = 15.66\ \%$$

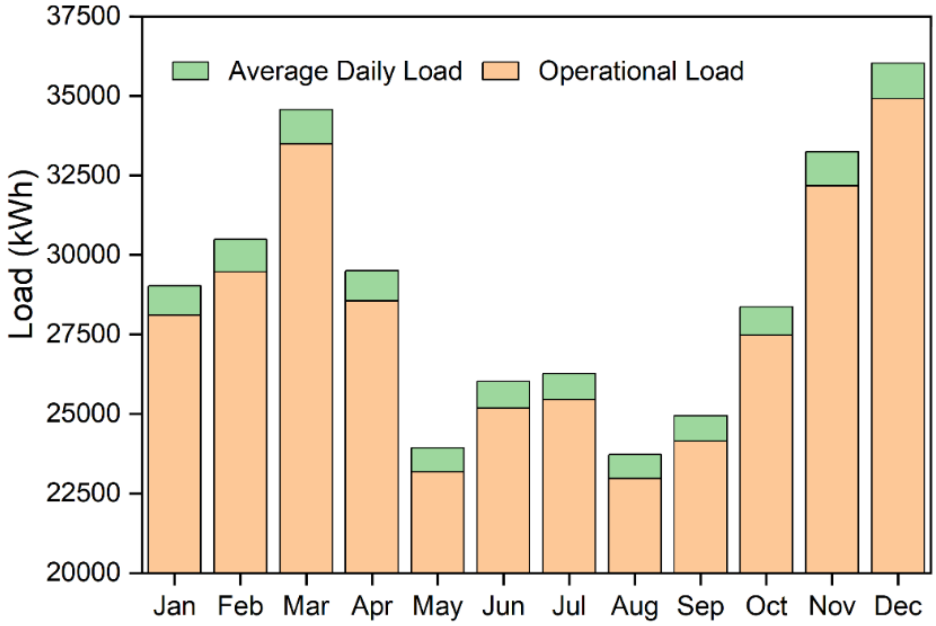

Figure 4. Operational load profile of the Tulungagung hydropower plant in 2024.

Technically, the on-grid solar power plant will contribute approximately 15.66% of the daily electricity requirement of the Tulungagung hydropower plant in 2024. However, because the average operational load significantly exceeds solar PV production, the solar power system primarily functions as a supporting energy source rather than as the main electricity supplier. The remaining 85% of the demand was met through electricity from PLN when the hydropower generator was not operational.

3.2. *Cost saving Tulungagung hydropower plant operation*

Operational cost savings arise from the electricity generated by the solar PV system, which reduces reliance on PLN's electricity supply. The applied electricity tariff was IDR 1,114.74 per kWh, classified under group I-3/TM [31]. The total operational load in 2024 was 335,150.71 kWh, resulting in an annual baseline operational cost of approximately IDR 373.6 million without the solar PV contribution.

Figure 5 illustrates the monthly operational costs for 2024, showing the variations in electricity consumption and expenses. The integration of a solar PV system offsets part of the load, thereby reducing operational costs and delivering economic benefits to the consumer. These cost savings underscore the feasibility of solar PV integration to support hydropower operations and decrease dependency on external electricity sources. The total operational electricity cost for the Tulungagung hydropower plant in 2024 was calculated as follows:

$$
\begin{aligned}
\text{Operational cost} &= \text{Total Operational Load} \times \text{Electricity rate per kWh} \\
&= 335150.71 \text{ kWh x IDR } 1114.74 \text{ per kWh} \\
&= \text{IDR } 373{,}605{,}902
\end{aligned}
$$

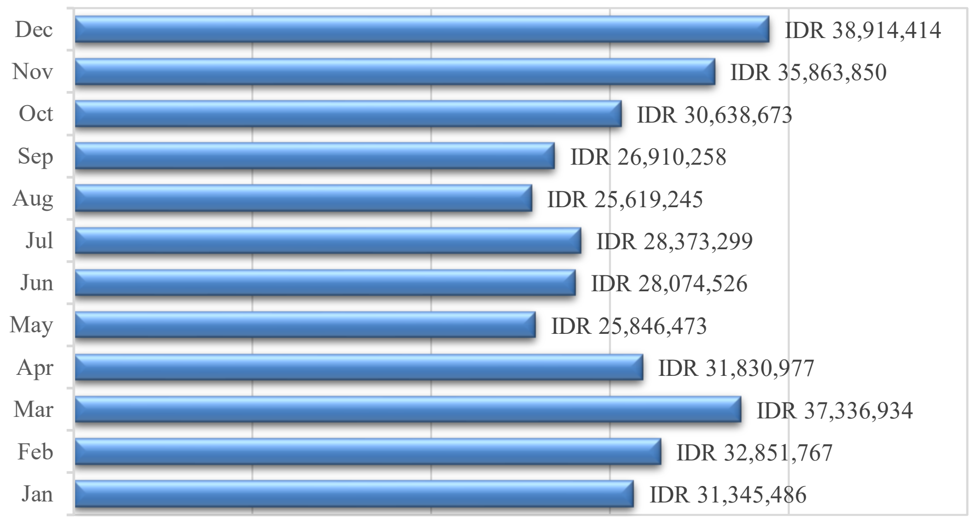

Figure 5. Monthly operational costs at the Tulungagung hydropower plant in 2024.

In 2024, the solar power plant produced 52,499.9 kWh, resulting in measurable economic savings. Using an electricity tariff of IDR 1,114.74 per kWh, the estimated savings amounted to IDR 58,523,260, representing a reduction in the costs that would otherwise be paid to PLN. Figure 6 shows the monthly distribution of these operational savings, illustrating how seasonal variations in the solar energy output affect the financial benefits of the solar PV system during the year.

The solar PV system produced 52,499.9 kWh in 2024, resulting in significant operational cost savings. With an electricity tariff of IDR 1,114.74 per kWh, these savings amounted to IDR 58,523,260. Figure 6 shows the monthly percentage distribution of savings, highlighting the role of solar PV systems in reducing the energy expenses. Fluctuations in savings are influenced by seasonal variations in solar irradiance and load demand, demonstrating the economic benefit of integrating solar PV into hybrid systems to enhance overall energy-cost efficiency.

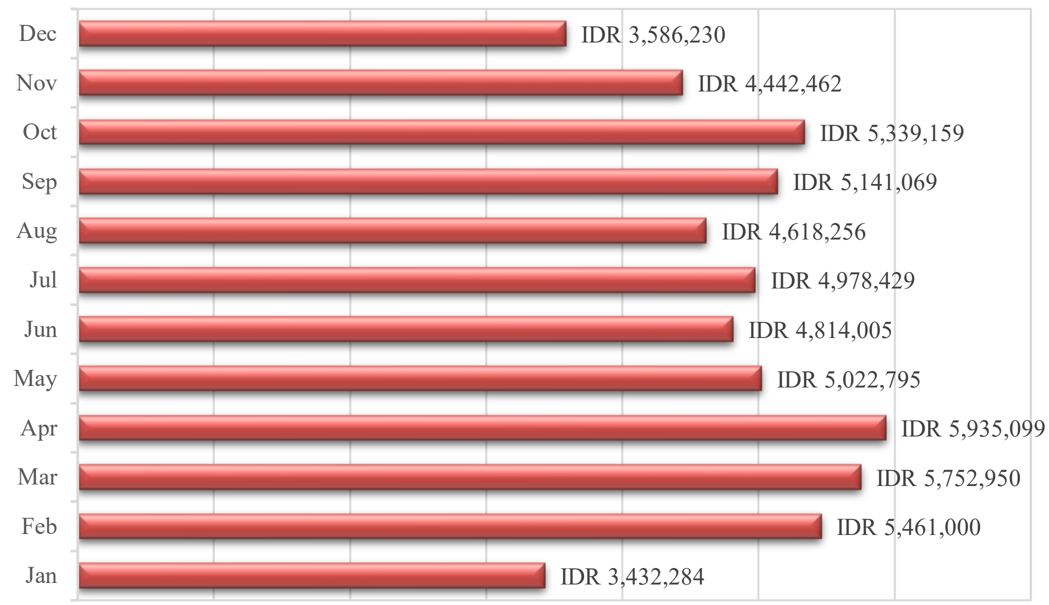

Figure 6. Monthly operational cost savings at the Tulungagung hydropower plant in 2024.

Figure 7 illustrates the monthly percentage contribution of the on-grid solar power plant to operational cost savings by 2024. The highest savings percentage was recorded in May (19.43%), which was attributed to a low operational load of 23,186.1 kWh, despite the peak solar PV production occurring in April (5,324.2 kWh). The lowest percentage occurred in December (9.22%) owing to reduced solar output (3,217.1 kWh) and a high operational load (34,908.96 kWh), highlighting the seasonal dependence of PLN on periods of low solar irradiance.

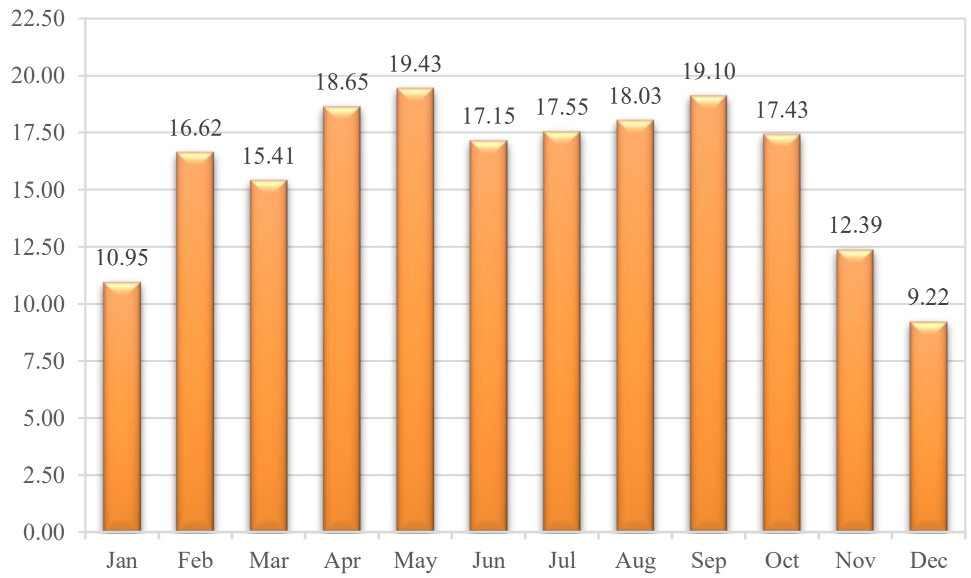

Figure 7. Monthly distribution of operating cost savings (%) at the Tulungagung hydropower plant in 2024.

From an economic standpoint, these percentage contributions translate into cost savings based on the PLN tariff of IDR 1,114.74 per kWh. Monthly savings peaked at IDR 5,022,795 in May and decreased to IDR 3,586,230 in December. The total savings for 2024 were estimated at IDR 58,523,260. Although the solar PV system contributed to approximately 15% of the total annual energy needs, this partial contribution demonstrates its economic viability as a supplementary source, effectively reducing reliance on PLN and supporting the cost efficiency of hydropower operations.

Overall, the integration of an on-grid solar power plant has proven to be technically feasible and economically advantageous for the Tulungagung hydropower plant. However, the currently installed capacity is insufficient to meet the full operational demand. Consequently, there is a continued reliance on hydropower generation and PLN electricity. Future improvements should focus on capacity expansion, energy storage integration, and load management strategies to optimize solar energy utilization and further reduce dependence on external power sources, particularly during periods of high demand or low-solar-radiation.

3.3. *Homer simulation results*

To further evaluate the technical and economic feasibility of the on-grid PV system integrated with the Tulungagung hydropower plant, a simulation study was conducted using HOMER software. HOMER enables the modeling of hybrid renewable energy systems under various operational scenarios and environmental conditions. In this study, software was used to simulate the energy output, grid interaction, and load fulfillment of the system over one year, based on the site-specific solar irradiance profile and load data. The results of the HOMER simulation are illustrated in Figure 8, and a summary of the technical simulation outcomes is presented in Table 4.

Architecture						Cost				System		330wp	
330wp (kW)	450wp (kW)	580wp (kW)	PLN (kW)	Gro39.85 (kW)	Dispatch	NPC (Rp)	LCOE (Rp/kWh)	Operating cost (Rp/yr)	CAPEX (Rp)	Ren Frac (%)	Total Fuel (L/yr)	CAPEX	Energy Production (kWh/yr)
14.9	16.2	9.86	999,999	39.9	CC	Rp6.46B	Rp1,142	Rp367M	Rp268M	1.77	0	126,000,000	23,932
14.9			999,999	39.9	CC	Rp6.47B	Rp1,147	Rp373M	Rp180M	0.00303	0	126,000,000	23,932
14.9		9.86	999,999	39.9	CC	Rp6.50B	Rp1,152	Rp372M	Rp214M	0.0951	0	126,000,000	23,932
14.9	16.2		999,999	39.9	CC	Rp6.51B	Rp1,153	Rp372M	Rp234M	0.266	0	126,000,000	23,932

Figure 8. HOMER simulation results for the on-grid PV system integrated with the Tulungagung hydropower plant.

Table 4. Summary of HOMER simulation technical results.

Parameter	Results
Total Production (kWh/year)	393,513
Network Production (kWh/year)	329,249
Solar PV production (kWh/year)	74,265
Energy Consumption (kWh/year)	335,179

Based on the simulation results presented in Table 4, the on-grid solar power plant generated an annual energy output of 74,265 kWh, and the total annual energy consumption was 335,179 kWh. The HOMER simulation yields important economic performance indicators, including a net present cost (NPC) of IDR 6,461,879,000, a levelized cost of energy (LCOE) of IDR 1,142.36 per kWh, and annual operational expenses totaling IDR 367,027,000. These metrics provide a comprehensive overview of the long-term economic feasibility of integrating solar power systems into existing hydropower infrastructure, as shown in Figure 9.

Total NPC:	IDR 6,461,879,000.00
Levelized COE:	IDR 1,142.36
Operating Cost:	IDR 367,027,000.00

Figure 9. Economic results of the HOMER simulation.

The discrepancy between the simulated and actual solar PV production primarily arises from site-specific weather variations at the Tulungagung hydropower plant. These climatic factors influence daily energy generation, leading to minor deviations in the technical output and cost-saving estimates. The HOMER simulation predicted a solar PV contribution of 16.33%, which was slightly higher than the measured average value of 15.66%. This difference highlights the importance of incorporating local meteorological data to enhance the simulation accuracy and optimize the system design and performance projections

3.4. *Discussion*

The integration of an on-grid solar PV system in the Tulungagung hydropower plant achieved an operational cost saving of approximately 15.66%, corresponding to an annual energy generation of 52,499.9 kWh against a total load demand of 335,150.71 kWh. Although this result is significant, it is comparatively modest when juxtaposed with those of prior studies reported in the literature (Table 1).

Hutajulu et al. [11] demonstrated a considerably higher load contribution of up to 60% with a performance ratio (PR) of 85% in an on-grid solar power plant in Ecopark, indicating that system scale and site-specific conditions critically influence PV output. Similarly, Aji et al. [12] reported cost savings of up to 22.1%, emphasizing the role of export-import dynamics in optimizing economic benefits. Adi et al. [17] and Dewi et al. [24] further confirmed that large-scale rooftop PV installations and optimized operational strategies can yield cost reductions exceeding 20% and 40%, respectively.

The seasonal variation in energy savings observed in Tulungagung, with the highest cost savings of 19.43% in May and the lowest of 9.22% in December, aligns with the findings of Sreenath et al. [18] and Gunoto & Hutapea [19], which underscores the influence of climatic factors, such as solar irradiance and temperature, on PV efficiency. The reduced performance during low-irradiation months highlights the necessity for adaptive load management and possible integration with energy storage to mitigate the intermittency.

The economic feasibility assessment via the HOMER simulation yielded a net present cost (NPC) of IDR 6.46 billion and a levelized cost of energy (LCOE) of IDR 1,142.36/kWh, which is comparable to the local grid tariff of IDR 1,114.74/kWh. This parity indicates competitive viability, although the gap between the simulated (74,265 kWh) and actual (52,499.9 kWh) energy generation suggests the need for calibration of the simulation inputs based on precise meteorological and operational data, which is consistent with the recommendations of Burhandono et al. [23].

The findings of this study highlight the opportunities for system enhancement through capacity expansion, improved system design, and energy storage integration. Previous research has shown that such improvements can substantially increase cost savings and renewable penetration rates [11,17, 24]. Moreover, incorporating environmental impact assessments, as proposed by Octavia et al. [21], can strengthen the sustainability profile of Tulungagung's hybrid system.

In conclusion, the Tulungagung case study affirms the potential of hybrid solar-hydropower systems for cost-effective renewable energy generation in Indonesia's regional contexts. Future studies should focus on optimizing the system scale and incorporating advanced management strategies to maximize economic and environmental benefits.

4. Conclusions

This study demonstrates that the 40.9 kWp on-grid solar power plant at the Tulungagung hydropower plant contributed 52,499.9 kWh of electricity in 2024, covering 15.66% of the total operational load of 335,150.71 kWh and resulting in annual cost savings of IDR 58,523,260. This was based on the PLN tariff of IDR 1,114.74/kWh. The HOMER simulation results estimated a slightly higher solar PV output of 74,265 kWh/year, with a net present cost (NPC) of IDR 6,461,879,000, cost of energy (COE) of IDR 1,142.36, and a solar contribution of 16.33%. The discrepancy between the simulated and actual values can be attributed to the idealized weather conditions assumed in the model, which did not reflect the reduced solar radiation during the rainy season. Although the solar power plant system has proven technically and economically beneficial, its current capacity is insufficient to meet full operational demands, necessitating continued reliance on PLN, particularly during high-load periods or when solar energy availability is low. These findings highlight the value of integrating solar PV as a supplementary energy source and suggest the need for further studies on expanding solar power plant applications at other hydropower sites, including the use of energy storage systems to enhance sustainability and independence from the grid.

Author's Declaration

Authors' contributions and responsibilities

The authors contributed significantly to the conception and design of this study. The corresponding author was responsible for the data analysis, interpretation, and discussion of the results. All authors have reviewed and approved the final version of the manuscript.

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Availability of data and materials

All data supporting the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no conflicts of interest related to this study.

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