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Techno-Economic Analysis of a 10 MW Floating Solar Photovoltaic System on Ranu Grati Lake: A HOMER Simulation Study

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Abstract: The techno-economic performance of a 10 MW floating photovoltaic (FPV) system on Lake Ranu Grati has been evaluated using HOMER Pro simulations, incorporating a representative medium-voltage load profile to assess feasibility under realistic operational conditions. The system is projected to generate approximately 15.35 GWh of electricity annually, with a capacity factor of 17.5%, demonstrating stable output under tropical irradiance patterns. The majority of the FPV-generated electricity is expected to supply local medium-voltage loads, while surplus energy will be exported to the national grid, resulting in a renewable energy share of approximately 80% throughout the year. Economic analysis indicates a Net Present Cost (NPC) of USD 12.9 million and a Levelized Cost of Energy (LCOE) of USD 0.053/kWh, both of which are competitive compared to the prevailing industrial electricity tariffs in Indonesia. The Internal Rate of Return (IRR) is calculated at 9.2%, with an estimated payback period of approximately 10 years. Environmentally, the FPV system is projected to reduce CO_2 emissions by around 11,000 tonnes per year, while simultaneously preserving land resources and enhancing the utilization of water surfaces. Overall, the Ranu Grati FPV project demonstrates strong technical performance, economic feasibility, and significant environmental benefits, making it a promising solution for Indonesia's transition towards sustainable energy.

Keywords: Floating photovoltaic; Techno-economic assessment; HOMER simulation; Grid-connected photovoltaic; Levelized Cost of Energy; Ranu Grati Lake, Indonesia; Renewable energy; Floating solar; Environmental impact

1 Introduction

The global demand for clean electricity is increasing due to the environmental impacts associated with the consumption of fossil fuels [1]. Solar photovoltaic (PV) technology has become one of the most effective renewable alternatives to address this challenge [2]. Among various PV applications, floating photovoltaic (FPV) systems—PV modules installed on water surfaces such as reservoirs and lakes—offer essential advantages, including reduced land use and improved energy efficiency due to the natural cooling effect of water [3]. FPV systems can also reduce water evaporation and suppress algal growth, thereby contributing to better water quality [4]. These benefits are particularly relevant for regions facing land limitations and growing renewable-energy needs, including East Java Province, where the installed capacity of solar power plants remains relatively limited compared to regional energy demand.

Accurate performance and economic assessment of FPV systems requires reliable modeling tools. HOMER Pro is widely used for comprehensive simulation and optimization of renewable energy systems [5]. Previous studies have shown that integrating FPV with hydropower can increase annual electricity production, reduce intermittency, and lower the Levelized Cost of Energy (LCOE) [6]. Other research has explored the combination of FPV with hydrogen storage, demonstrating its potential to form fully renewable energy systems for industrial applications and remote communities [7].

Numerous techno-economic studies have evaluated FPV performance using indicators such as Net Present Cost (NPC), LCOE, and emission reductions [8]. Comparative assessments generally report that FPV can outperform land-based PV in terms of energy output and cost-effectiveness, especially in locations with high irradiance or limited land availability [9]. Several large-scale FPV projects in Indonesia have also shown promising feasibility results [10]. At the same time, HOMER-based analyses further confirm that FPV installations on reservoirs can deliver stable and competitive electricity generation [11]. However, most previous studies did not incorporate regional demand characteristics or site-specific operational contexts.

In the present study, the load profile used is not derived from direct field measurements but is constructed from representative demand patterns commonly applied in medium-voltage system analyses. This approach is widely accepted in techno-economic modeling when long-term measured load data are unavailable, and still allows the simulation to reflect realistic consumption behavior.

Based on this background, this study evaluates the technical and economic performance of a 10 MW FPV system at Lake Ranu Grati, Pasuruan, Indonesia. The findings aim to provide insights into the practical and sustainable implementation of FPV in tropical regions, while supporting increased solar deployment in East Java. A summary of recent FPV studies is presented in Table 1.

Table 1. Summary of recent studies on floating photovoltaic (FPV) systems

Method/Approach	Location	Main Findings	Comparative Insight	Reference
Techno-economic and sensitivity analysis using HOMER Pro	Bangladesh (river islands), 2–5 MW	Net Present Cost (NPC) ≈ USD 2.3 M; Levelized Cost of Energy (LCOE) ≈ 0.036 USD/kWh; FPV feasible for off-grid communities	Off-grid context; high sensitivity to solar uncertainty	[12]
Techno-economic feasibility using RETScreen	Cirata Reservoir, Indonesia, 145 MW	Internal Rate of Return (IRR) ≈ 11%; Payback ≈ 9 years; large-scale FPV feasible	Uses RETScreen (simplified model); focuses on utility-scale FPV without load integration	[13]
Techno-economic analysis of photovoltaic (PV)/ wind turbine /biomass hybrid system using HOMER	Northern Morocco (rural area)	Demonstrates the feasibility of a hybrid PV/wind turbine /biomass system	Not FPV; hybrid multi-source system; rural electrification context	[14]
Techno-economic modeling of hybrid FPV-hydropower using HOMER Pro	Guatamela	FPV improves reliability, reduces LCOE, and stabilizes output	FPV integrated with hydropower; not standalone FPV	[15]
Techno-economic analysis using HOMER Pro	Surakarta, Indonesia, 25 kWp	LCOE ≈ 0.031 USD/kWh; competitive with Perusahaan Listrik Negara (PLN) tariff	Small-scale rooftop/land PV; no floating design; different scale	[16]
This study	Ranu Grati Lake, Indonesia—10 MW FPV	Technical-economic evaluation using HOMER Pro with an assumed representative Medium Voltage load profile	First Indonesian FPV study evaluating 10 MW capacity using a realistic assumed load pattern, bridging the gap between generic models and local demand characteristics	-

2 Methodology

This study presents a techno-economic assessment to determine the feasibility of a 10 MW floating solar PV system on Lake Ranu Grati. The study methodology encompasses various parameters, including site characterization, system design optimization, solar resource evaluation, load profile analysis, and economic analysis using HOMER Pro. By following a systematic methodology, the technical and financial variables of the FPV system are thoroughly examined to determine its feasibility under existing climatic and economic conditions.

2.1 Research Flow Chart

The overall operation of the FPV system is presented in Figure 1, which depicts the sequence of energy flow from solar irradiation to grid interaction. In this configuration, sunlight is captured by the PV modules and converted into direct current (DC) electricity. The inverter subsequently converts the DC output into alternating current (AC) for supplying local loads, while any surplus energy is exported to the Perusahaan Listrik Negara (PLN) grid.

Figure 1 highlights the essential stages of energy conversion and distribution, deliberately omitting auxiliary elements such as monitoring, protection, and control components for simplicity. This schematic effectively illustrates how the FPV installation maintains continuous interaction with the grid and delivers stable renewable power despite fluctuations in solar availability.

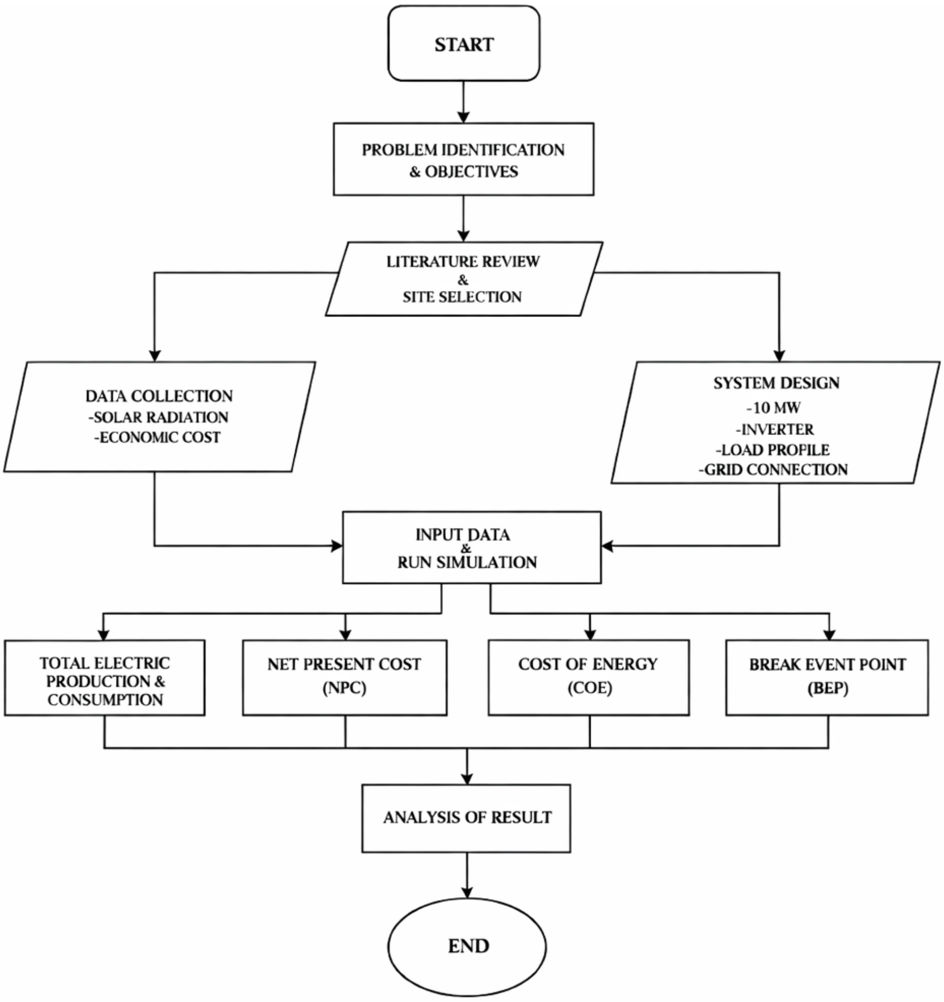

Figure 1. Methodology flowchart of the floating photovoltaic (FPV) study

2.2 Research Location and Object

The research was conducted in the beautiful Lake Ranu Grati of Pasuruan Regency, District of Grati, East Java Province, Indonesia. The geographical location of the study area is shown in Figure 2. The natural freshwater lake occupies approximately 107 hectares and is 200 meters above sea level [17]. The landscape comprises agricultural fields, rural towns, and rolling hills, making it a peaceful and suitable location for renewable energy development, particularly FPV systems [18]. Geologically, the lake was formed through ancient volcanic eruptions, creating a stable basin with peaceful hydrodynamic properties that are ideal for floating solar farms [19].

Figure 2. Location Ranu Grati Lake

Ranu Grati also serves as a vital resource for the local community, supporting fisheries, aquaculture, irrigation, and tourism. Therefore, the FPV project should be closely managed to maintain these activities in equilibrium and avoid potential land-use conflicts [20]. The regional tropical monsoon climate features temperatures ranging from 24°C to 32°C and annual rainfall of 1,500–2,000 mm. The region's climatic conditions, high solar irradiance, flat water surfaces, and gentle winds favor FPV energy production [21, 22].

Proximity to towns and the presence of PLN grid infrastructure facilitate the efficient transmission of electricity and grid integration [23]. Socioeconomically, Pasuruan Regency has exhibited steady growth in energy demand for residential, industrial, and agricultural uses. Due to the limited land area capacity for massive ground-mounted PV projects, Lake Ranu Grati offers a strategic and sustainable solution that maximizes space efficiency and improves local energy security [24].

At $07°43'56.08''$ S and $113°00'51.32''$ E coordinates, the site's accessibility, favorable solar potential, and safe environment make it an ideal case to emulate for future deployment of FPV and Indonesian renewable energy development.

Although the site shows strong suitability for FPV deployment, several limitations should be noted. Seasonal and annual climate variability may affect long-term energy output beyond the simulated period. Floating components such as pontoons and mooring systems may experience degradation over time, which was not modeled in this study. Potential ecological impacts on the lake, such as changes in water temperature or aquatic conditions, were also not assessed. The key technical assumptions and system parameters adopted in this study are summarized in Table 2. These factors define the boundaries of this analysis and indicate the need for future investigation.

Table 2. Key site parameters and study limitations (concise version)

Parameter	Value/Description
Location	Lake Ranu Grati, Pasuruan Regency, East Java
Surface area	∼107 hectares
Elevation	∼200 m above sea level
Climate	Tropical monsoon; 24–32°C; 1,500–2,000 mm rainfall
Solar potential	High irradiance suitable for floating photovoltaic (FPV)
Water condition	Calm water surface; stable volcanic basin
Grid availability	Connected to the Perusahaan Listrik Negara (PLN) distribution network
Key limitations	Climate variability, potential floating-structure degradation, and ecological uncertainties

2.3 Description of the PLTS (Solar PV System) Design Model (on-Grid)

The suggested 10 MW FPV station at Lake Ranu Grati Pasuruan is designed as an on-grid power station integrated with the PLN (State Electricity Company) grid connection. The design allows for a safe and steady supply of electricity. Solar radiation is first converted to DC by PV modules and subsequently converted to AC by inverters to supply to nearby customers. The grid connection enables two-way power flow, allowing for the export of excess power to PLN during periods of high production and the import of electricity when generation is low, such as at night or on cloudy days [25]. The overall configuration and power flow of the proposed on-grid FPV system are illustrated in Figure 3.

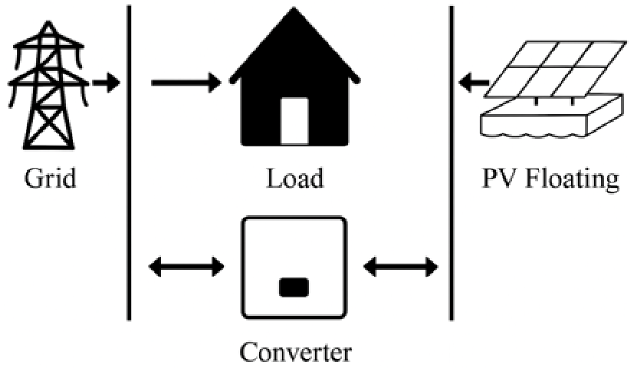

Figure 3. Floating photovoltaic (FPV) design system in Homer Pro

The system has four key components: floating PV arrays, inverter units, local loads, and the PLN grid. The floating configuration enhances efficiency by utilizing water cooling, reducing evaporation, and conserving land space [26]. Inverters manage power conversion and synchronization with the grid [27], while local loads are residential, commercial, and industrial users in Pasuruan.

The PLN grid serves as both a source of energy and a destination for redundant power, thereby maintaining equilibrium in the system. FPV operates on a daily cycle—meeting most of the load, exporting surplus during peak sunlight, balancing the load during moderate irradiance, and relying on PLN during nighttime. It eliminates mass energy storage, lowering costs while maintaining dependability [28]. The techno-economic performance was modeled using HOMER Pro software, taking into account aspects such as NPC, LCOE, and Break Even Point (BEP) to ascertain feasibility and competitiveness [29, 30]. At a global level, the system contributes to local energy resilience and supports Indonesia's transition towards renewable energy.

2.4 Potential Use of Solar Energy

To assess the solar energy potential at Lake Ranu Grati, this study utilized data from the Global Solar Atlas (2025), which provides monthly Global Horizontal Irradiance and Direct Normal Irradiance values. These values were cross-checked with the SARAH-3 satellite dataset to ensure accuracy under tropical conditions [31]. Seasonal Direct Normal Irradiance variations reflect East Java's monsoon climate, with higher solar intensity in the dry season and lower values during the wet months [32].

Table 3. Potential use of solar energy

Mounth	Irradiation (kWh/m^2)
January	86.8
February	82.5
March	106.3
April	124.8
May	150.8
June	154.1
July	176.1
August	193.8
September	190.3
October	119.1
November	169.3
December	83.2

As shown in Table 3, the highest Direct Normal Irradiance occurs in August (193.8 kWh/m^2) and the lowest in February (82.5 kWh/m^2), confirming that Ranu Grati has consistently strong solar resources suitable for FPV development. These irradiation datasets serve as key inputs for HOMER Pro simulations and underpin the projected energy yield of the system.

2.5 Economic and Financial Assumptions

Table 4 presents the cost assumptions used in the simulation with HOMER Pro. The initial capital of the FPV plant—PV modules, floating structure, balance of system (BOS) components, engineering, and installation—is estimated at USD 12.0 million. Another USD 0.8 million is spent on the inverter unit, so the total capital expenditure (CAPEX) of the 10 MW FPV plant is around USD 12.8 million. Annual operation and maintenance (O&M) expense expense for the PV array is approximately USD 150,000, and that of the inverter is USD 15,000.

These inputs on cost are in line with international cost benchmarks developed by the International Renewable Energy Agency, as well as ASEAN Centre for Energy reports that specify similar investment scales for FPV projects in Southeast Asia [33, 34]. Collectively, these costs as estimated form a legitimate basis upon which the project's economic viability can be determined in the HOMER Pro simulation.

Table 4. Cost assumptions used in the simulations

Component	Cost (USD)	Remarks
Photovoltaic (PV) System (modules, floating structure, balance of system (BOS), installation & engineering)	12,000,000	Total cost of a 10 MW floating PV system
Inverter (10 MW, bidirectional)	800,000	Separate cost for the power conversion system
Total capital expenditure (CAPEX)	12,800,000	Overall investment cost of the project
Annual PV operation and maintenance (O&M)	150,000/year	Estimated O&M cost of the PV system
Annual Inverter O&M	15,000/year	The estimated O&M cost of the inverter

2.6 System Specifications and Design Parameters

FPV systems comprise solar panels mounted on floating platforms above bodies of water. The system is helpful in several aspects, including improved panel efficiency due to the natural cooling offered by water, reduced evaporation rates, and reduced land use [35]. In this study, a 10 MW FPV plant was modeled using HOMER Pro software, considering an initial investment of USD 12 million and an annual O&M cost of USD 150,000. The plant has been designed for a 25-year commercial life with an 85% derating factor, a module efficiency of 17–18%, and a tilt angle of 10° to 15°. Although floating PV systems typically require 10–15% more upfront costs than land-based PV systems, their high performance and land-space savings make floating PV systems economically viable for tropical regions [36].

In HOMER-based analysis, project economic viability is measured primarily by NPC and Cost of Energy (COE). NPC is the system lifetime cost, and COE is the average cost per kilowatt-hour of produced energy. These parameters provide a comprehensive view of system cost-effectiveness and serve as benchmarks for comparing different FPV configurations.

2.6.1 The equation calculating the NPC

$$\mathrm{NPC} = \frac{C_{ann,tot}}{\mathrm{CRF}\left(i, R_{proj}\right)} \tag{1}$$

where, $C_{ann,tot}$ is the total annualized cost of the system (USD/year), including capital, replacement, O&M, and other associated costs; Capital Recovery Factor (CRF) is the capital recovery factor; i is the real annual discount rate; R_{proj} is the project lifetime (year).

2.6.2 COE

COE or LCOE represents the average cost per kilowatt-hour of electricity generated throughout the system's operational period. It is obtained by dividing the total annualized cost by total energy production.

The COE can be calculated using the equation:

$$\mathrm{COE} = \frac{C_{ann,tot}}{E_{prim,AC} + E_{prim,DC}} \tag{2}$$

where, $E_{prim,AC}$ is the annual primary AC electrical energy supplied to the load (kWh/year); $E_{prim,DC}$ is the annual primary DC electrical energy supplied to the load (kWh/year).

2.6.3 BEP

BEP indicates the time required for the project to recover its initial investment from cumulative net profits. A shorter BEP reflects a faster return on investment and higher economic attractiveness.

The BEP can be estimated using the following expression:

$$\mathrm{BEP} = \frac{\text{Total Investment}}{\text{Annual Net Cash Flow}} \tag{3}$$

2.7 FPV System

FPV refers to a new generation of solar power technology in which PV panels are installed on floating platforms that float over bodies of water. FPV installations offer numerous benefits over conventional ground-mounted installations, including greater efficiency due to the water-cooling effect, lower evaporation rates, and reduced land use.

Based on the HOMER Pro simulation presented in Table 5, the simulated FPV system in this work has an installed capacity of 10 MW, a total investment cost of USD 12.0 million, and an annual O&M cost of USD 150,000. The design incorporates an 85% derating factor and a 25-year lifespan, and the investment encompasses PV modules, floating structures, anchoring mechanisms, and BOS components. These adhere to international standards for large-scale deployment of FPV, and current studies confirm that FPV systems have 5–10% more annual energy output than ground-based PV systems under the same solar conditions [37].

Hence, the 10 MW FPV power plant on Lake Ranu Grati can be regarded as both technically and economically feasible, particularly in areas where land resources are scarce but water surface areas are abundant. This case demonstrates the promise of FPV systems as a sustainable and scalable means of introducing solar energy capacity in Indonesia.

Table 5. Parameter photovoltaic (PV) in HOMER

Parameter	Value	Unit	Description
Rated capacity	10,000	kW	Installed PV capacity in the simulation
Capital cost	12,000,000	USD	Includes items (excluding the inverter): PV modules, floats, wiring, mounting, and balance of system (BOS)
Replacement cost	-	-	Not considered in the simulation
Operation and maintenance (O&M) cost	150,000	USD/year	Annual O&M cost
Lifetime	25	year	Project and component design lifetime
Derating factor	8	%	Accounts for temperature, dust, and wiring losses
Efficiency	∼17–18	%	Average PV module efficiency assumed
Tilt angle	10–15	°	Based on a floating structure design
Azimuth	0 (South)	°	Oriented to maximize annual irradiation

2.8 Converter (Inverter)

The inverter (HOMER Pro converter) is a key component that converts the DC output of the PV modules into grid-compatible AC power. The system utilizes a 10 MW converter with an initial capital cost of USD 800,000, an annual O&M cost of USD 15,000, and a replacement cost of USD 800,000 due to its shorter lifespan compared to PV modules. The inverter has a 12-year design life and achieves 98% efficiency in both inverter and rectifier modes, which is consistent with utility-scale standards [38]. As presented in Table 6, the inverter parameters include capacity, cost components, lifetime, and efficiency values used in the HOMER Pro simulation.

Table 6. Parameter converter

Parameter	Value	Unit
Capacity	10,000	kW
Capital cost	800,000	USD
Replacement cost	800,000	USD
Operation and maintenance (O&M) cost	15,000	USD/year
Lifetime	12	Year
Inverter efficiency	98	%
Rectifier efficiency	98	%

Unlike PV modules, which include floating structures and BOS costs, the inverter is treated as a separate cost category to maintain accurate system architecture and lifecycle assessment. Since inverters require replacement during the 25-year project life, their modular design and high efficiency help minimize conversion losses, supporting overall system reliability and economic performance.

2.9 Electric Load Profile

The simulated system load profile is illustrated in Table 7 and Figure 4. The average daily load for the system is approximately 24,000 kWh, and the average demand is 1,000 kW, peaking at 2,576 kW; thus, the load factor is 0.39. The minimum demand occurs in the morning (approximately 667 kW) and increases steadily after 06:00, when domestic and commercial loads are resumed. Demand is greater between 09:00 and 16:00, with a range of 1,500 to 2,500 kW, and dwindles towards late evening as the power load decreases.

Table 7. Daily load distribution and total consumption

WIB	kW	Hours	kWh	Load (%)	Description
00:00–03:00	700	4	2,800	11.7	Base load (low demand)
04:00–06:00	950	3	2,850	11.9	Beginning of load increase
07:00–09:00	1,400	3	4,200	17.5	Morning activity increases
10:00–16:00	2,000	7	14,000	58.3	Peak load during the daytime
17:00–20:00	1,250	4	5,000	20.8	Evening consumption remains high
21:00–23:00	800	3	2,400	10.0	Nighttime demand decreases
Total	-	24	24,000	100	As scaled in HOMER Pro

Note: Time is given in Waktu Indonesia Barat (WIB), GMT+7

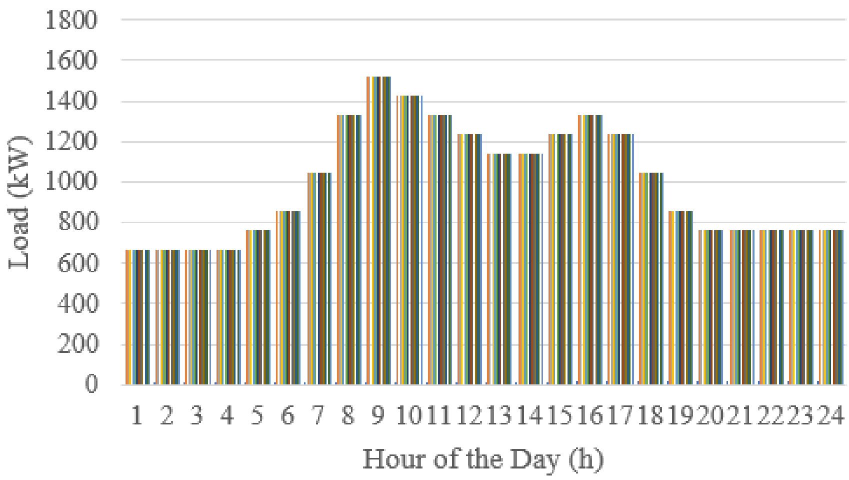

Figure 4. Grafik daily load profile

This is characteristic of the high commercial and residential energy consumption regimes, where most consumption is during the day and closely follows the solar generation profiles. This synchronism between demand and PV generation maximizes the efficiency of FPV system operation by minimizing energy mismatch and grid reliance during the day. FPV power generation is the top priority when supplying local loads under simulation. Excess power is provided to the grid, and shortages are automatically met by drawing power from it; hence, there is a round-the-clock and assured power supply throughout the day.

This table shows that the daytime peak period (10:00–16:00) accounts for more than half of the daily consumption (58.3%), followed by the evening load (20.8%) and the morning load (17.5%). The lowest demand occurs at night (10–12% of the total). This distribution highlights the strong alignment between peak demand and solar generation potential, reinforcing the effectiveness of integrating floating PV in meeting daily load requirements.

2.10 Grid Connection

The FPV system operates as a grid-connected installation, enabling two-way electricity exchange with the PLN network. When solar generation is insufficient, electricity is imported from the grid, while surplus generation is exported. For the economic simulation, this study applies a non-subsidized industrial medium-voltage electricity tariff of Indonesian Rupiah (IDR) 1,114.74/kWh (≈USD 0.0719/kWh), in accordance with the PLN electricity tariff determined by the Ministry of Energy and Mineral Resources for the 2023–2024 period [39].

As the basis for determining the selling price of exported electricity, this study refers to Ministerial Regulation of Ministry of Energy and Mineral Resources No. 49 of 2018, under which exported renewable electricity is compensated at 65% of the applicable PLN tariff, equivalent to approximately IDR 725/kWh (≈USD 0.0467/kWh). Both the purchase and export tariffs are directly implemented in the HOMER Pro model. Because the export tariff is lower than the purchase tariff, maximizing self-consumption becomes a critical factor in improving the economic feasibility of the FPV project [40].

3 Result

3.1 Technical Performance of the FPV System

The 10 MW FPV power plant at Lake Ranu Grati demonstrates stable performance throughout the year, indicating strong suitability for tropical regions. Seasonal irradiance patterns—higher in the dry season and lower during the rainy months—cause corresponding fluctuations in monthly output. Despite these variations, the annual generation remains consistent, supporting the regional electricity supply.

Simulation results indicate that the system generates approximately 15.35 GWh of electricity annually. Part of this energy is used to supply the local medium-voltage loads, while the surplus is exported to the PLN grid. According to the HOMER Pro results (Table 8), the FPV system exports about 10.04 GWh/year and imports around 3.75 GWh/year during nighttime or periods of low irradiance. The renewable fraction of 80% indicates that, over the year, roughly 80% of the total load energy is supplied by the FPV system and the remaining 20% by the grid.

Table 8. Simulation results

Parameter	Unit	Value	Description
Photovoltaic (PV) capacity	kW	10,000	Installed solar array capacity
Annual PV production	kWh/a	15,352,955	Total annual solar energy generated
Energy sold to grid	kWh/a	10,039,698	Surplus electricity is exported to the Perusahaan Listrik Negara (PLN) grid
Energy purchased from grid	kWh/a	3,753,802	Electricity is imported from PLN during low solar output
Renewable fraction	%	80.0	Share of total load met by renewable generation
Initial capital cost	USD	12,800,000	Total investment for PV and balance of system (BOS) components
Net Present Cost (NPC)	USD	12.900,000	Total discounted project lifetime cost
Levelized Cost of Energy (LCOE)	USD/kWh	0.053	Average lifetime cost of energy production
Operating cost	USD/yr	6,346	Annual operation and maintenance (O&M) expenses

The floating configuration enhances performance through natural water-based cooling, which reduces thermal losses and improves module efficiency compared with ground-mounted systems. The alignment between PV generation and daytime demand also minimizes curtailment and increases self-consumption. Economically, the system achieves an LCOE of USD 0.053/kWh and an NPC of USD 12.88 million, confirming its feasibility under Indonesia's prevailing tariff conditions. Overall, the Lake Ranu Grati FPV project demonstrates strong technical and economic performance in a tropical climate.

Figure 5 shows the monthly electricity output of the FPV system. Generation increases from January and reaches its highest levels from July to September during the dry season, when solar irradiance is strongest. This seasonal trend reflects the strong influence of tropical solar irradiance conditions on FPV system performance. Reduced energy production during the rainy months is primarily caused by increased cloud cover, higher atmospheric moisture, and more frequent rainfall, which limit solar radiation reaching the PV modules. In contrast, the dry season offers clearer skies and longer effective sunshine hours, resulting in higher monthly electricity generation. Despite these seasonal variations, the overall production profile remains relatively stable without sharp declines, indicating reliable system operation. This stability is beneficial for grid-connected applications, as it supports more predictable energy planning and enhances the contribution of FPV systems to local electricity supply throughout the year.

To evaluate the interaction between supply and demand, the system output was compared with the daily load profile shown in Figure 6. The load profile used in this study is assumed, not measured data. Because actual load measurements were not available at the project site, the load curve was developed using standard load-shape patterns commonly applied in Indonesian distribution networks. The profile was then scaled to represent a typical mixed-load condition (residential, commercial, and light industrial) in the Pasuruan Regency area.

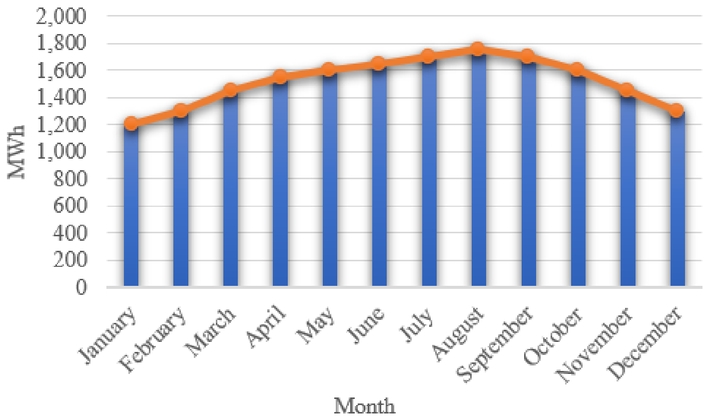

Figure 5. Grafik monthly photovoltaic (PV) energy production

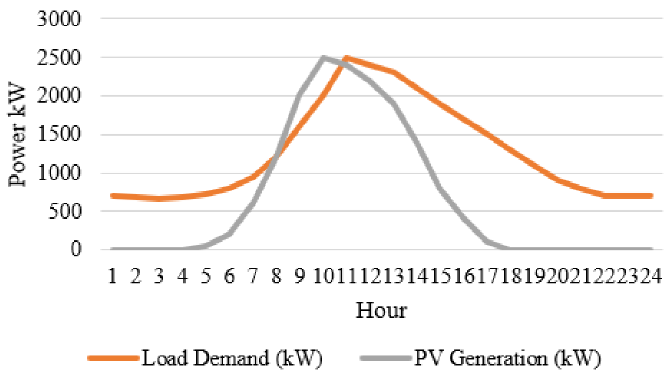

Figure 6. Average daily load vs photovoltaic (PV) generation profile

This approach maintains transparency regarding data limitations while still providing a realistic approximation of local demand behavior. Although the profile does not represent actual measured consumption, it offers a credible basis for assessing how the FPV system can support daytime loads and reduce dependence on PLN grid imports.

The average daily energy demand is approximately 24,000 kWh, equivalent to an average load of about 1,000 kW and a peak of 2,576 kW. Demand is lowest in the early morning (approximately 667 kW), increases after 06:00, and reaches its maximum between 09:00 and 16:00. This pattern closely matches the peak of FPV generation, enabling a substantial portion of daytime demand to be supplied directly by solar energy.

To further assess the efficiency of the FPV system, key operational parameters have been evaluated based on simulation results from the HOMER Pro. These parameters capture the system's conversion of solar energy into electrical output, consistent performance, and overall installed capacity utilization. It can be seen that the values reflect the 10 MW FPV plant at Lake Ranu Grati's stable annual generation and reliable capacity factor under tropical conditions, revealing an efficient system output and resource exploitation every year. Detailed parameters are tabulated in Table 9.

Table 9. Output parameters from simulation

Parameter	Value	Description
Installed capacity	10,000 kW	Total photovoltaic (PV) system capacity
Annual generation	15.35 GWh	Electricity generated by the PV system
Capacity factor	17.5%	Utilization of installed capacity
Operating hours	4,281 h	System operating time per year

3.2 Economic Analysis

The Lake Ranu Grati 10 MW FPV system was economically evaluated using the financial outputs of the HOMER Pro simulation. Both CAPEX and operational expenditure were included to assess the long-term feasibility of the project. The total initial investment is approximately USD 12.8 million, consisting of USD 12.0 million for the FPV array (including floating structure, anchoring system, and balance of system) and USD 0.8 million for the inverter and power conversion units. The annual O&M cost for the PV array and inverter is estimated at USD 165,000. Based on these inputs, the simulation yields a NPC of USD 12.9 million and a LCOE of USD 0.053/kWh. The detailed component cost structure of the FPV system is presented in Table 10.

Table 10 reports only the lifecycle costs of the physical components of the FPV plant, namely the FPV array and the inverter. The PLN grid is not shown as a separate cost component because it functions as an external electricity exchange mechanism rather than a physical asset of the system. In the HOMER Pro model, the financial benefit from electricity export to the grid is treated at the system level and directly reflected in the overall NPC, rather than being allocated to an individual component. Under the PLN medium-voltage industrial tariff of approximately IDR 1,114.74/kWh (USD 0.0719/kWh) and an export price equal to 65% of this tariff, the FPV system produces electricity at a cost about 26% lower than the grid purchase price, confirming its strong economic viability.

Table 10. Component cost summary of the 10 MW floating photovoltaic (FPV) system

Component	Capital	Replacement	Operation and Maintenance (O&M)	Fuel	Salvage	Total
FPV array	12,000,000.00	0.00	1,399,127.48	0.00	0.00	13,399,127.48
Inverter	800,000.00	605,828.60	139,312.75	0.00	-175,675.67	1,214,065.59
System total	12,800,000.00	605,828.60	1,538,440.23	0.00	-175,675.67	12,900,000.00

3.3 Economic Results

3.3.1 NPC

NPC represents the total cost incurred over the system's lifetime, encompassing capital, replacement, operating, and maintenance expenses. Based on the revised simulation, the FPV system costs USD 12.9 million. This is an economic necessity in the long run to manage the 10 MW floating solar system, demonstrating that the design is economically viable even for large-scale renewable projects. HOMER sets this design as optimal to balance cost and performance over the project's duration. The detailed economic results are summarized in Table 11.

Table 11. Economic results

Parameter	Value	Unit	Description
Net Present Cost (NPC)	12.9	million USD	Total lifetime system cost
Levelized Cost of Energy (LCOE)	0.053	USD/kWh	Average cost per unit of energy
Net Present Value (NPV)	1.9	million USD	Profit after discount rate
Internal Rate of Return (IRR)	9.2	%	Project profitability indicator
Break Even Point (BEP)	10.1	year	Time required to recover investment
Total capital expenditure (CAPEX)	12.8	million USD	Initial investment cost
Annual operation and maintenance (O&M) Cost	0.165	million USD	Yearly O&M cost
Annual Net Cash Flow	0.95	million USD	Net profit per year after O&M
Annual energy output	15.35	GWh	Electricity generated per year
Lifetime energy output	383.75	GWh	Total generation over 25 years

3.3.2 LCOE

LCOE represents the average cost incurred over the project's duration to produce one kilowatt-hour of electricity. Simulation has yielded a LCOE value of USD 0.053/kWh, which is lower compared to the PLN medium-voltage industrial tariff of approximately IDR 1,114.74/kWh (USD 0.0719/kWh) as per the Ministry of Energy and Mineral Resources Regulation No. 28/2016 and No. 26/2021. This demonstrates that the Lake Ranu Grati FPV power plant can produce clean electricity at a cost approximately 26% lower than the grid purchase tariff, confirming its strong economic performance.

3.3.3 Net Present Value (NPV)

NPV calculates the project's profitability as a ratio of total discounted costs to revenues. The updated simulation yields an NPV of USD 1.9 million at an 8% discount rate, again demonstrating that FPV is a profitable investment and a good return on investment throughout its operational life.

3.3.4 IRR

IRR measures profitability in relation to the initial investment. The IRR of the FPV system is 9.2%. In comparison, the assumed discount rate is 8%, a slight increase, indicating that the project remains financially profitable in real-world situations and pays investors adequately.

3.3.5 BEP

BEP is the time required to break even by recovering the original investment through net profits each year. The simulation calculates a payback period of 10.1 years, indicating that the project can recoup its capital in the first half of its 25-year project lifespan, which affirms its financial viability in the medium term.

3.4 Sensitivity Analysis

A brief sensitivity assessment was conducted to identify which input parameters in HOMER Pro exert the most decisive influence on the NPC and LCOE in Table 12. Since CAPEX constitutes the most significant portion of the project's lifetime cost, variations in PV investment cost have the most significant impact on both NPC and LCOE. Higher CAPEX increases the annualized capital charge, thereby raising NPC and LCOE almost proportionally.

The discount rate is also a major driver of LCOE because it directly affects the capital recovery factor used in the annualized cost calculation. An increase in the discount rate results in higher annualized capital costs, leading to a notable rise in LCOE, while its impact on NPC is comparatively more minor. Meanwhile, variations in annual O&M expenses have a moderate influence, given their smaller share of lifetime costs.

Changes in solar resource availability—represented by the capacity factor—mainly influence LCOE because reduced generation spreads fixed costs over fewer kilowatt-hours. Overall, PV CAPEX and the discount rate are the most sensitive parameters, followed by O&M costs and variations in solar resources.

Table 12. Sensitivity of key input parameters on Net Present Cost (NPC) and Levelized Cost of Energy (LCOE)

Parameter	Impact on NPC	Impact on LCOE	Explanation
Photovoltaic (PV) total capital expenditure (CAPEX)	High	High	Capital cost dominates lifetime expenditure; changes directly affect annualized cost and overall project economics.
Discount rate	Moderate	High	Strong influence on the capital recovery factor used in LCOE calculation; NPC is less sensitive than LCOE.
Operation and maintenance (O&M) cost	Low-moderate	Low-moderate	A smaller portion of the total cost; variations have a limited but noticeable influence over the project's lifetime.
Solar resource/ capacity factor	Low	Moderate	Affects annual energy production; LCOE increases when generation decreases, while NPC remains relatively unchanged.
Inverter replacement cost	Low	Low-moderate	Replacement occurs only at specific intervals; influence is secondary compared to PV CAPEX and discount rate.

4 Discussion

The techno-economic evaluation finds that the proposed 10 MW FPV power plant at Lake Ranu Grati is economically and technically feasible. The revised simulation yields a LCOE of USD 0.053/kWh, which is significantly lower than the PLN industrial medium-voltage tariff of USD 0.0719/kWh (approximately IDR 1,114.74/kWh) applied in 2023–2024. This indicates that the FPV system remains competitive under real market conditions. The project requires an NPC of USD 12.9 million, achieves an IRR of 9.2%, and offers a payback period of about 10.1 years. At an 8% discount rate, the system yields an NPV of USD 1.9 million, demonstrating its long-term economic viability.

Despite the higher initial cost of floating structures, the system remains feasible due to strong energy output and the absence of land-use conflicts. Technically, the FPV plant can generate approximately 15.35 GWh of electricity per year, supplying a significant portion of daytime demand around the lake. Its production profile closely matches the regional load curve, helping reduce grid dependence during peak periods.

Seasonal variation in irradiance results in slightly higher generation during the dry season and lower output during the wet season. However, the system still achieves a positive net annual export, ensuring a consistent contribution to renewable energy throughout the year.

Beyond economic and technical performance, the FPV installation provides environmental and spatial co-benefits. It preserves land, reduces water evaporation, suppresses algae growth, and decreases CO_2 emissions by about 11,000 tonnes per year. These advantages support the FPV system's role in Indonesia's clean energy transition. Overall, the 10 MW Ranu Grati FPV project stands as a robust, sustainable, and replicable model for the deployment of inland-water renewable energy.

5 Conclusion

This study demonstrates that the 10 MW FPV system at Lake Ranu Grati is technically, economically, and environmentally feasible under Indonesia's current energy conditions. The HOMER Pro simulation results show stable annual generation of 15.35 GWh, with system output aligning well with daytime demand patterns. Although the load profile used in this study is an assumed curve based on standard Indonesian distribution load shapes, the results indicate that the FPV system can reliably support local daytime consumption and reduce dependence on PLN grid imports.

The project achieves an NPC of USD 12.9 million and an LCOE of USD 0.053/kWh, which remains below the prevailing industrial medium-voltage tariff. Financial indicators—including an NPV of USD 1.9 million, an IRR of 9.2%, and a payback period of around 10 years—confirm strong investment viability. Beyond its economic merits, the FPV installation offers additional benefits, including land-use savings, reduced water evaporation, improved panel efficiency through water-based cooling, and an estimated annual reduction of approximately 11,000 tonnes of CO_2 emissions. These advantages reinforce the role of FPV technology as a strategic option to support Indonesia's energy transition and sustainable development goals.

Overall, the Lake Ranu Grati FPV project serves as a promising and scalable model for inland-water solar deployment, demonstrating a balanced integration of technical performance, economic competitiveness, and environmental sustainability.

Author Contributions

Conceptualization, R. P.; methodology, R. P.; software, R. P.; validation, R. P.; formal analysis, R. P.; investigation, Rama Pujangga; resources, R. P.; data curation, R. P.; writing—original draft preparation, R. P; writing—review and editing, R. P.; visualization, M. Z. A.; supervision, R. P.; project administration, R. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare no conflicts of interest.

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