Jurnal Engine:
Energi, Manufaktur, dan Material

Vol.10 No.1 Mei 2026 hal: 070 - 082

Planning Analysis and Efficiency Comparison of On-Grid, Off-Grid, and Hybrid Grid-Tied Rooftop Solar Power Systems for the Development of the Control Building of Perum Jasa Tirta 1/3, WS Brantas Division

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Article Info: *Received: April 12, 2026; Accepted: May 14, 2026; Available online: May 19, 2026*
DOI: *10.30588/jeemm.v10i1.2676*

Abstract: *Perum Jasa Tirta I, WS Brantas Division in the Tulungagung working area, experiences unreliable electricity supply due to frequent outages, requiring an alternative solution through a rooftop photovoltaic (PV) system. This study aims to design and evaluate the performance and techno-economic feasibility of three configurations: On-Grid, Off-Grid, and Hybrid Grid-Tied systems. Based on the energy consumption analysis, the total demand is 233.5 kWh/day or 85,192.10 kWh/year. By considering system losses of 25% and an Equivalent Sun Hours (ESH) value of 4.5 hours/day, the required PV capacity is 69.18 kW, using 93 modules of 750 Wp. Simulation results using Homer Pro show that the On-Grid system generates 166,208 kWh/year, the off-grid system produces 123,361 kWh/year, and the hybrid grid-tied system generates 140,699 kWh/year. All systems are capable of meeting the load demand, with different levels of energy surplus. From a techno-economic perspective, the off-grid system provides the highest return with an NPV of IDR 11.2 billion and an IRR of 128%, but it is relatively overdesigned and highly dependent on batteries. The on-grid system offers lower investment costs but depends on the utility grid. Meanwhile, the hybrid system shows balanced performance and is considered the optimal solution.*

Keywords: *Rooftop Solar Power Plant, Renewable Energy, Techno-Economic Analysis, Homer Pro Simulation, Energy Reliability*

I. Introduction

The increasing demand for electrical energy in operational buildings, driven by the growth of work activities, requires a reliable, efficient, and sustainable energy supply system. In general, electricity demand is still fulfilled by the utility grid, resulting in a high dependency on conventional energy sources [1]. This condition may lead to significant problems, particularly in locations that frequently experience power outages. Such issues are also encountered in the operational building of Perum Jasa Tirta I (PJT I), WS Brantas Division in the Tulungagung working area, which plays a vital role in water resources management, including the operation of Wonorejo Dam. Therefore, an alternative energy system is required to improve the reliability of electricity supply [2],[3]. The utilization of renewable energy, particularly solar energy through rooftop photovoltaic (PV) systems, is considered a promising solution. Indonesia, as a tropical country, has relatively high solar irradiation throughout the year, making it suitable for PV implementation [4],[5]. Rooftop PV systems offer several advantages, including no requirement for additional land, reduction of electricity consumption from the grid, and contribution to carbon emission reduction. Furthermore, the implementation of PV systems supports the transition toward a cleaner and more sustainable energy system [6],[7].

In practice, rooftop PV systems can be configured into several types, namely On-Grid, Off-Grid, and Hybrid Grid-Tied systems [8],[9]. The On-Grid system is directly connected to the utility grid without battery storage, making it simpler and more economical, but still dependent on the grid [10],[11]. The Off-Grid system operates independently using battery storage, increasing energy autonomy but requiring higher investment costs [12],[13]. Meanwhile, the Hybrid Grid-Tied system combines PV, battery storage, and the utility grid to enhance system reliability and flexibility [14],[15]. Each configuration has different characteristics, thus requiring a comprehensive analysis to determine the most suitable system. Previous studies have indicated that the selection of PV system configuration is influenced by load profiles, geographical conditions, and economic factors such as Net Present Value

(NPV) and Internal Rate of Return (IRR) [16],[17],[6]. However, studies specifically comparing these three configurations in operational buildings with particular reliability requirements are still limited, especially in water resource management institutions such as PJT I. Therefore, further investigation is necessary to evaluate the performance and feasibility of each system.

Based on these considerations, this study aims to design and analyze the performance and techno-economic feasibility of rooftop PV systems with On-Grid, Off-Grid, and Hybrid Grid-Tied configurations for the operational building of PJT I WS Brantas Division in Tulungagung. Unlike previous studies, as shown at **Table 1** below, this research incorporates actual operational load conditions, reliability requirements due to frequent grid disturbances, and energy surplus potential into the system evaluation using Homer Pro. The novelty of this study lies in the comprehensive comparison of three PV system configurations under a real-world operational scenario of water resource infrastructure, emphasizing the trade-off between energy reliability, system autonomy, and economic feasibility. The results are expected to provide a more practical and applicable decision-making basis for selecting the optimal PV system configuration in similar critical infrastructure environments.

Table 1. Summary of State-of-the-Art Previous Studies on Photovoltaic Systems and Techno-Economic Analysis

Reference	Method	Key Finding
[18]	Economic and environmental assessment of grid-connected rooftop PV system using Homer Pro, considering roof area, load profile, and grid export/import.	The system generated around 160,000 kWh/year of clean electricity and significantly reduced emissions, including 101,353 kg CO_2 annually, demonstrating both economic and environmental benefits of on-grid PLTS.
[19]	Techno-economic analysis of Off-Grid PV–diesel hybrid system for rural electrification using Homer Pro, considering LCOE and life-cycle cost.	The 100% PV with battery system resulted in the lowest LCOE, while standalone diesel showed high operational costs. This study proves that renewable-based off-grid systems are more economically sustainable in remote areas.
[20]	Comprehensive review study of grid-connected solar PV optimization, covering component sizing, inverter topology, tilt angle, and LCOE optimization.	The study highlights that optimization of PV module arrangement, inverter selection, and tilt angle strongly affects system efficiency and can reduce the LCOE of large-scale grid-connected PV plants to around $0.03/kWh.
[21]	Techno-economic modeling of stand-alone PV system using IEEE sizing standard + Homer Pro sensitivity analysis under different fuel costs.	The stand-alone PV system showed 64% lower LCOE than diesel generation, with a payback period of 5.5 years, confirming the technical and economic feasibility of off-grid solar systems.
[22]	Performance improvement study of rooftop grid-connected PV system using PVsyst simulation, shading analysis, and annual energy yield evaluation.	The proposed rooftop design reduced shading losses by 11–13% and increased grid-injected energy by 40 MWh/year, with a performance ratio increase from 0.704 to 0.791.

II. Method

Planning object data was collected through direct observation during the internship and interviews with employees of the Public Company Jasa Tirta I WS Brantas Division to ensure that the rooftop Solar Power Plant design is in accordance with the actual conditions of the building.

1. Flowchart

This study employs a structured methodology by integrating field observation, literature review, and simulation to analyze the performance of rooftop photovoltaic (PV) systems. Data were collected through direct site observation, including interviews and assessment of the existing operational building conditions, and supported by literature review as the theoretical foundation and design reference. Meteorological data such as solar irradiation and temperature were used as primary parameters, followed by the selection of system components including PV modules, inverters, and supporting equipment. The system was then modeled using Homer Pro to evaluate technical performance and energy production under On-Grid, Off-Grid, and Hybrid Grid-Tied configurations. The simulation results were further analyzed through technical and economic approaches, including evaluation of energy production, system efficiency, and financial feasibility. This method ensures that each stage is interconnected, resulting in accurate, comprehensive, and reliable analysis to support optimal PV system selection can be seen in the **Figure 1** below.

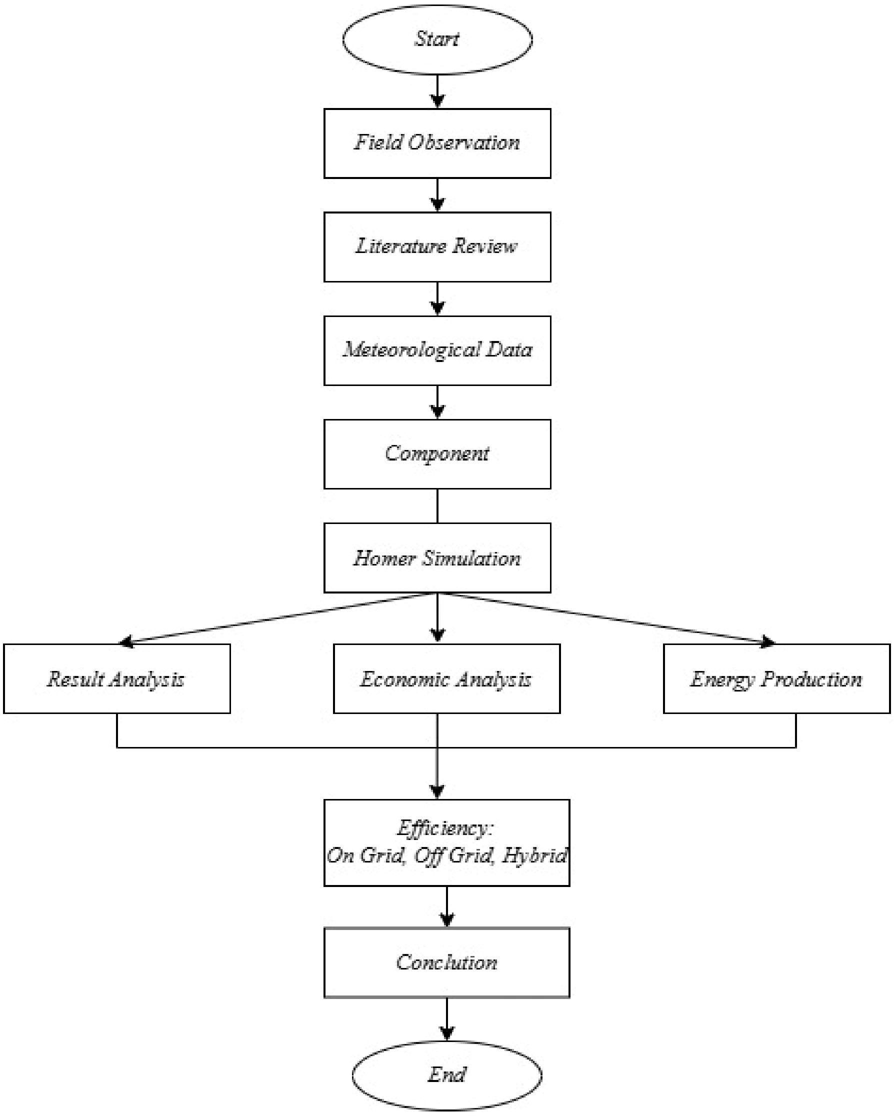


Figure 1. Flowchart

2. Geographical Studies

The geographic study in this report uses data from the Climatology Station located at the Wonorejo Dam. Irradiation data can be seen in **Table 2-Table 4** below.

Table 2. Climatology Data from Wonorejo Station for January

Date	Temperature				Evaporation Mm	Weather			Sunlight Time	Average Weather
	07	13	18	Average		07	13	18		
01	24.70	28.40	26.40	26.50	0.43	Rain	Rain	Cloudy	1.30	Rain
02	24.70	29.30	26.70	26.90	0.67	Bright	Rain	Bright	2.00	Bright
03	23.80	29.70	26.10	26.53	1.00	Bright	Cloudy	Bright	3.00	Cloudy
04	25.30	25.70	26.80	25.93	0.67	Bright	Rain	Bright	2.00	Rain
05	23.80	32.70	26.70	27.73	0.67	Bright	Cloudy	Cloudy	2.00	Cloudy
06	24.80	30.30	23.80	26.30	1.00	Cloudy	Bright	Rain	3.00	Bright
07	24.60	31.30	23.90	26.60	0.67	Cloudy	Bright	Rain	2.00	Bright
08	23.70	32.20	24.50	26.80	1.43	Bright	Bright	Rain	4.30	Bright
09	24.30	25.00	24.90	24.73	0.43	Bright	Rain	Rain	1.30	Rain
10	23.80	28.70	25.90	26.13	0.67	Cloudy	Bright	Cloudy	2.00	Cloudy
11	24.90	25.80	26.00	25.57	0.00	Cloudy	Rain	Cloudy	0.00	Cloudy

12	24.70	28.90	24.80	26.13	0.67	Bright	Cloudy	Cloudy	2.00	Cloudy
13	25.30	30.40	27.30	27.67	0.67	Bright	Bright	Bright	2.00	Bright
14	24.70	29.60	26.80	27.03	0.67	Bright	Cloudy	Cloudy	2.00	Cloudy
15	24.40	33.10	25.00	27.50	0.67	Bright	Cloudy	Cloudy	2.00	Cloudy
16	23.30	29.40	25.50	26.07	1.00	Bright	Cloudy	Bright	3.00	Bright
17	24.60	30.10	26.50	27.07	0.43	Bright	Cloudy	Bright	1.30	Bright
18	25.40	32.00	24.40	27.27	0.33	Bright	Cloudy	Rain	1.00	Cloudy
19	24.00	30.00	24.40	26.13	0.67	Cloudy	Cloudy	Cloudy	2.00	Cloudy
20	23.80	31.20	25.00	26.67	0.73	Cloudy	Cloudy	Cloudy	2.20	Cloudy
21	23.60	30.40	23.90	25.97	0.43	Cloudy	Cloudy	Rain	1.30	Cloudy
22	23.20	31.20	23.80	26.07	0.00	Cloudy	Cloudy	Rain	0.00	Cloudy
23	23.70	29.00	24.50	25.73	0.00	Cloudy	Cloudy	Cloudy	0.00	Cloudy
24	24.10	28.70	24.70	25.83	0.00	Cloudy	Cloudy	Cloudy	0.00	Cloudy
25	23.40	30.30	26.70	26.80	0.00	Cloudy	Cloudy	Cloudy	0.00	Cloudy
26	23.80	31.20	26.10	27.03	0.00	Cloudy	Cloudy	Cloudy	0.00	Cloudy
27	24.30	28.50	25.00	25.93	0.00	Cloudy	Cloudy	Rain	0.00	Cloudy
28	25.00	29.70	24.70	26.47	0.67	Bright	Cloudy	Rain	2.00	Cloudy
Average	26,6 °C				0,53 mm/day				1,8 hour/day	

Table 3. Climatology Data from Wonorejo Station for February

Date	Temperature				Evaporation Mm	Weather			Sunlight Time	Weather Average
	07	13	18	Average		07	13	18		
01	24.70	28.40	26.40	26.50	0.43	Rain	Rain	Cloudy	1.30	Rain
02	24.70	29.30	26.70	26.90	0.67	Bright	Rain	Bright	2.00	Bright
03	23.80	29.70	26.10	26.53	1.00	Bright	Cloudy	Bright	3.00	Cloudy
04	25.30	25.70	26.80	25.93	0.67	Bright	Rain	Bright	2.00	Rain
05	23.80	32.70	26.70	27.73	0.67	Bright	Cloudy	Cloudy	2.00	Cloudy
06	24.80	30.30	23.80	26.30	1.00	Cloudy	Bright	Rain	3.00	Bright
07	24.60	31.30	23.90	26.60	0.67	Cloudy	Bright	Rain	2.00	Bright
08	23.70	32.20	24.50	26.80	1.43	Bright	Bright	Rain	4.30	Bright
09	24.30	25.00	24.90	24.73	0.43	Bright	Rain	Rain	1.30	Rain
10	23.80	28.70	25.90	26.13	0.67	Cloudy	Bright	Cloudy	2.00	Cloudy
11	24.90	25.80	26.00	25.57	0.00	Cloudy	Rain	Cloudy	0.00	Cloudy
12	24.70	28.90	24.80	26.13	0.67	Bright	Cloudy	Cloudy	2.00	Cloudy
13	25.30	30.40	27.30	27.67	0.67	Bright	Bright	Bright	2.00	Bright
14	24.70	29.60	26.80	27.03	0.67	Bright	Cloudy	Cloudy	2.00	Cloudy
15	24.40	33.10	25.00	27.50	0.67	Bright	Cloudy	Cloudy	2.00	Cloudy
16	23.30	29.40	25.50	26.07	1.00	Bright	Cloudy	Bright	3.00	Bright
17	24.60	30.10	26.50	27.07	0.43	Bright	Cloudy	Bright	1.30	Bright
18	25.40	32.00	24.40	27.27	0.33	Bright	Cloudy	Rain	1.00	Cloudy
19	24.00	30.00	24.40	26.13	0.67	Cloudy	Cloudy	Cloudy	2.00	Cloudy
20	23.80	31.20	25.00	26.67	0.73	Cloudy	Cloudy	Cloudy	2.20	Cloudy
21	23.60	30.40	23.90	25.97	0.43	Cloudy	Cloudy	Rain	1.30	Cloudy
22	23.20	31.20	23.80	26.07	0.00	Cloudy	Cloudy	Rain	0.00	Cloudy
23	23.70	29.00	24.50	25.73	0.00	Cloudy	Cloudy	Cloudy	0.00	Cloudy
24	24.10	28.70	24.70	25.83	0.00	Cloudy	Cloudy	Cloudy	0.00	Cloudy
25	23.40	30.30	26.70	26.80	0.00	Cloudy	Cloudy	Cloudy	0.00	Cloudy
26	23.80	31.20	26.10	27.03	0.00	Cloudy	Cloudy	Cloudy	0.00	Cloudy
27	24.30	28.50	25.00	25.93	0.00	Cloudy	Cloudy	Rain	0.00	Cloudy
28	25.00	29.70	24.70	26.47	0.67	Bright	Cloudy	Rain	2.00	Cloudy
Average	26,6 °C				0,53 mm/day				1,8 hour/day	

Table 4. Climatology Data from Wonorejo Station for March

Date	Temperature				Evaporation mm	Weather			Sunlight Time	Weather Average
	07	13	18	Average		07	13	18		
01	24.00	32.00	26.60	27.53	0.10	Bright	Cloudy	Cloudy	0.30	Cloudy
02	24.70	30.00	24.50	26.40	0.00	Cloudy	Cloudy	Cloudy	0.00	Cloudy
03	24.00	31.30	24.50	26.60	0.00	Rain	Cloudy	Rain	0.00	Rain

04	23.00	31.80	23.30	26.03	1.67	Cloudy	Bright	Bright	5.00	Bright
05	26.60	26.10	28.00	26.90	0.67	Bright	Rain	Bright	2.00	Bright
06	27.40	32.50	25.40	28.43	1.43	Bright	Bright	Rain	4.30	Bright
07	26.10	32.20	26.00	28.10	1.33	Bright	Bright	Rain	4.00	Bright
08	23.50	31.80	25.60	26.97	1.00	Bright	Bright	Bright	3.00	Bright
09	23.70	30.30	23.90	25.97	1.00	Bright	Bright	Rain	3.00	Bright
10	25.70	29.90	27.70	27.77	1.00	Bright	Rain	Bright	3.00	Bright
11	27.00	30.30	27.00	28.10	1.00	Bright	Rain	Bright	3.00	Bright
12	27.70	31.90	28.00	29.20	0.67	Bright	Bright	Bright	2.00	Bright
13	27.00	31.40	27.80	28.73	1.00	Bright	Bright	Bright	3.00	Bright
14	27.20	32.30	26.60	28.70	1.00	Bright	Bright	Bright	3.00	Bright
15	24.20	27.00	25.40	25.53	0.67	Bright	Bright	Bright	2.00	Bright
16	24.80	31.40	24.80	27.00	0.10	Rain	Cloudy	Rain	0.30	Rain
17	24.40	29.40	26.30	26.70	0.67	Bright	Bright	Bright	2.00	Bright
18	24.60	31.60	26.70	27.63	1.00	Bright	Bright	Bright	3.00	Bright
19	24.10	32.30	26.80	27.73	1.67	Bright	Bright	Bright	5.00	Bright
20	25.20	31.90	26.40	27.83	0.67	Bright	Bright	Bright	2.00	Bright
21	25.00	32.00	26.60	27.87	1.33	Bright	Bright	Bright	4.00	Bright
22	24.70	30.60	26.70	27.33	0.43	Bright	Cloudy	Bright	1.30	Bright
23					0.00					
24					0.00					
25					0.00					
26					0.00	Bright	Cloudy	Cloudy		Cloudy
27					0.00	Cloudy	Cloudy	Rain		Cloudy
28					0.00	Cloudy	Rain	Rain		Rain
29					0.00	Bright	Cloudy	Cloudy		Cloudy
30					0.00					
31					0.00					
Average	27,41°C				0,88 mm/day				2,83 hour/day	

Based on climatological data from the Wonorejo Dam Station during January to March, the temperature remains relatively stable in the range of 26.6–27.41°C, indicating optimal operating conditions for photovoltaic modules. Meanwhile, solar irradiation duration shows fluctuations, with an average of 2.5 hours/day in January, decreasing to 1.8 hours/day in February due to cloudy and rainy conditions, and increasing to 2.83 hours/day in March. This trend is consistent with evaporation values, which are lowest in February (0.53 mm/day) and highest in March (0.88 mm/day), reflecting variations in solar energy potential. Overall, February represents the lowest solar potential, while March shows the most favorable conditions. Therefore, the implementation of On-Grid or Hybrid Grid-Tied PV systems is recommended to ensure energy supply reliability during periods of reduced solar generation. The January to March climatology data represents observations during the practical period at the research site. This data is used to support the environmental conditions of the research site. Meanwhile, the solar power plant system simulation uses annual solar radiation data from the Global Solar Atlas, which is input into Homer Pro to obtain annual energy simulation results.

3. Irradiation Data

Other data used by the author is from the Global Solar Atlas. The data produced can be seen in **Table 5** below.

Table 5. Global Solar Atlas Irradiance Data

MAP DATA (Per *Year*)	
Specific photovoltaic power output	1280.3 kWh/kWp
Direct normal irradiation	911.2 kWh/m2
Global horizontal irradiation	1586.3 kWh/m2
Diffuse horizontal irradiation	909.8 kWh/m2
Global tilted irradiation at optimum angle	1595.8 kWh/m2
Optimum tilt of PV modules	9 / 0°
Air temperature	23.1 °C
Terrain elevation	697 m

Based on the Global Solar Atlas data, the research location has good solar energy potential for rooftop photovoltaic system development. The Global Horizontal Irradiation (GHI) value of 1586.3 kWh/m²/year was used as the primary solar radiation parameter in the Homer Pro simulation because GHI represents the total solar radiation received on a horizontal surface and is commonly applied in photovoltaic system analysis. In addition, the Global Tilted Irradiation (GTI) value of 1595.8 kWh/m²/year indicates that the solar radiation received by PV modules at the optimum tilt angle is relatively high, supporting electrical energy production. The specific photovoltaic power output value of 1280.3 kWh/kWp/year indicates that the research location has good potential for annual electrical energy generation. Furthermore, the optimum PV module tilt angle of approximately 9° is suitable for the geographical conditions of Indonesia. With an average air temperature of 23.1 °C and an elevation of 697 m above sea level, the environmental conditions at the research location are considered supportive for rooftop Solar Power Plant system performance.

4. Rooftop Solar Power Plant Design Scheme

The data obtained above can be used to design a rooftop solar power plant. Therefore, the solar power plant must be installed above the specified values. This is to avoid future load increases and to anticipate energy loss due to dust, heat, etc. A 25% decrease is typically observed [23], so the estimated required solar power plant capacity is:

$$233{,}5 : (100\% - 25\%) \tag{1}$$

$$\approx 311{,}33\ kWh \tag{2}$$

Based on the total daily electrical energy consumption in the building to be generated of 389,005 kWh/day and the Equivalent Sun Hours in Indonesia of 4.5 hours per day [24], the power requirements to be generated by the Solar Power Plant system are as follows [25]:

$$Solar\ Power\ Requirements = \frac{Total\ Energy\ Needs\ (kWh)}{Equivalent\ Sun\ Hours} \tag{3}$$

$$= \frac{311{,}33}{4{,}5} \tag{4}$$

$$= 69{,}18\ kW \tag{5}$$

So the number of solar panels required is as follows [26]:

$$Number\ of\ Solar\ Panels = \frac{Power\ Requirement\ (kWh)}{Solar\ Panel\ Module\ Capacity\ (Wp)} \tag{6}$$

$$= \frac{69{,}18\ kW}{750\ Wp} \tag{7}$$

$$= 93\ Solar\ Panels \tag{8}$$

From the calculation of the daily electrical energy requirement of 233.5 kWh, adjustments were made by taking into account system losses of 25%, resulting in an energy requirement of 311.33 kWh/day. Assuming Equivalent Sun Hours of 4.5 hours per day, the solar power requirement is approximately 69.18 kW. By using a solar module with a capacity of 750 Wp, the number of solar panels required is approximately 93 units. Then, for inverter selection, the author chose the Huawei SUN2000-75K-TL-C1 because it fits the number of solar panels used. According to its specifications, the inverter is 75 kW.

Rooftop Solar Power Plant design scheme for this report, as stated earlier, the author uses Homer Pro as a comparison between these three systems, as in the subsub points below.

4.1 On-Grid Rooftop Solar Power Plant

The design scheme for a rooftop Solar Power Plant can be seen in **Figure 2** below. Based on the diagram, the rooftop Solar Power Plant is designed sequentially, starting with solar modules installed on the roof surface as the primary source of DC electrical energy. This energy is then channeled through a wiring circuit to an inverter to be converted into AC current to meet the load requirements. The inverter output is then distributed to the main distribution panel to supply the building's electrical load and is integrated with the existing network, enabling the system to operate synchronously.

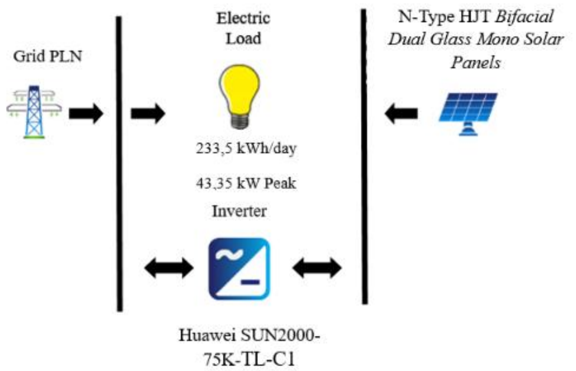


Figure 2. On-Grid Rooftop Solar Power Plant Design Scheme

This rooftop solar power plant design scheme demonstrates a simple yet efficient energy flow, with an emphasis on connectivity between key components such as modules, inverters, and distribution systems, thus supporting optimal solar energy utilization in buildings.

4.2 Off-Grid Rooftop Solar Power Plant

The design scheme for an Off-Grid Rooftop Solar Power Plant can be seen in **Figure 3** below. The figure shows a simulated Off-Grid Solar Power Plant system scheme consisting of several main components, namely a conventional electricity source (generator) on the left side, a solar panel (PV) system as the main renewable energy source, an inverter as a DC to AC current converter, and 3 unit of 100 kWh batteries as energy storage. The energy flow in this system is indicated by the direction of the arrows connecting each component, where energy from the PV will be used to supply the load and excess energy can be stored in the battery. Meanwhile, the conventional electricity source serves as a backup when PV production is insufficient. Overall, this configuration is designed.

To calculate battery capacity [27], see the equation below:

$$E_{load} = 233{,}5\ kWh/day \tag{9}$$

Assuming the battery DoD is 80% [28], then:

$$E_{battery} = \frac{233{,}5}{0{,}8} = 291{,}875\ kWh \tag{10}$$

From the calculation results above, the author chose a battery capacity of 300 kWh (with a configuration of 100 kWh for 3 units) to meet daily load requirements and provide a system safety margin, also to improve system reliability and optimize the use of renewable energy with the support of storage systems and power backup.

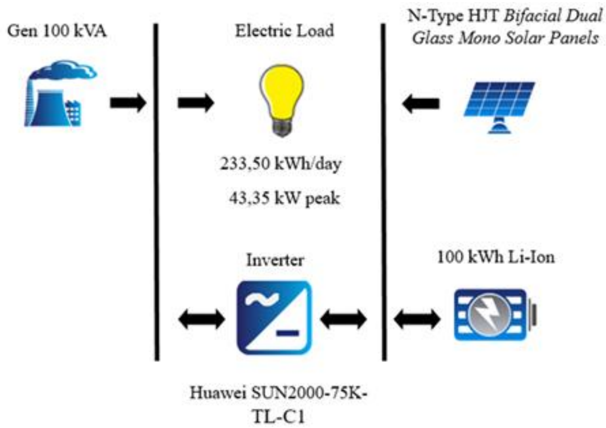


Figure 3. Off-Grid Rooftop Solar Power Plant Design Scheme

This rooftop solar power plant design scheme demonstrates a simple yet efficient energy flow, with an emphasis on connectivity between key components such as modules, inverters, and distribution systems, thus supporting optimal solar energy utilization in buildings.

4.3 Hybrid Grid-Tied Rooftop Solar Power Plant

The design scheme for the Hybrid Grid-Tied Rooftop Solar Power Plant, can be seen in **Figure 4** below. The figure shows the schematic of the Hybrid Grid-Tied Solar Power Plant system, where the system is directly connected to the National Electricity Company electricity grid as the main source and energy reserve. In this configuration, electrical energy is generated by solar panels (PV) in the form of DC current which is then converted by the inverter into AC current to supply an electrical load of 233.50 kWh/day with a peak load of 43.35 kW. In addition, the system is equipped with a 100 kWh battery (3 units) that functions as energy storage when PV production is excessive and can be reused when production decreases. The National Electricity Companyacts network as a balancer, namely supplying the power shortage when energy from PV and batteries is insufficient, and allows the system to remain stable and reliable in meeting load needs. Overall, this system optimizes the use of solar energy with grid support to improve the continuity and efficiency of electricity supply.

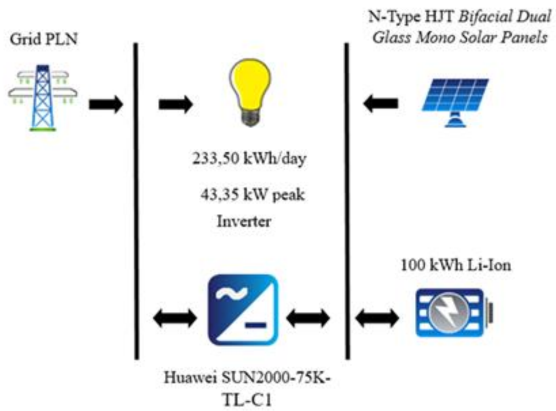


Figure 4. Hybrid Grid-Tied Rooftop Solar Power Plant Design Scheme

III. Results and Discussion

The results of the simulation and performance analysis of the rooftop solar PV system that have been carried out using Homer Pro are presented and discussed in the section below.

1. Energy Production and Consumption Analysis

Based on the simulation results of On-Grid, Off-Grid, and Hybrid Grid-Tied Rooftop Solar Power Plants using Homer Pro, the author obtained the results that can be seen in **Table 6** below.

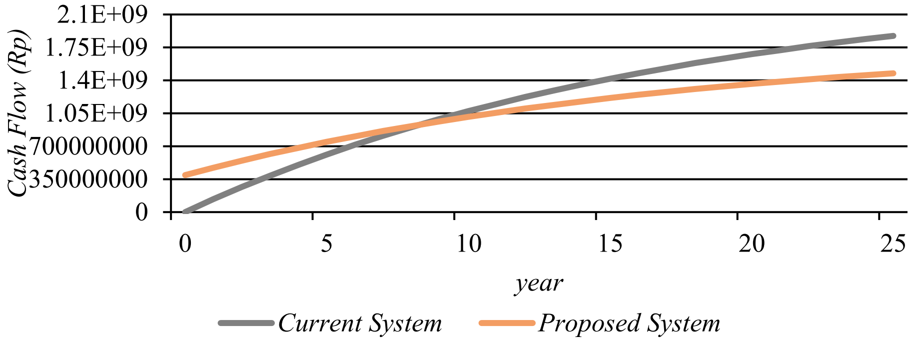
Table 6. Value of Production and Consumption Results

System	*Annual Production*	*Annual Consumption*
On-Grid	166,208 Kwh/year	163,798 Kwh/year
Off-Grid	123,361 kWh/year	85,228 kWh/year
Hybrid Grid-Tied	140,699 Kwh/year	135,537 Kwh/year

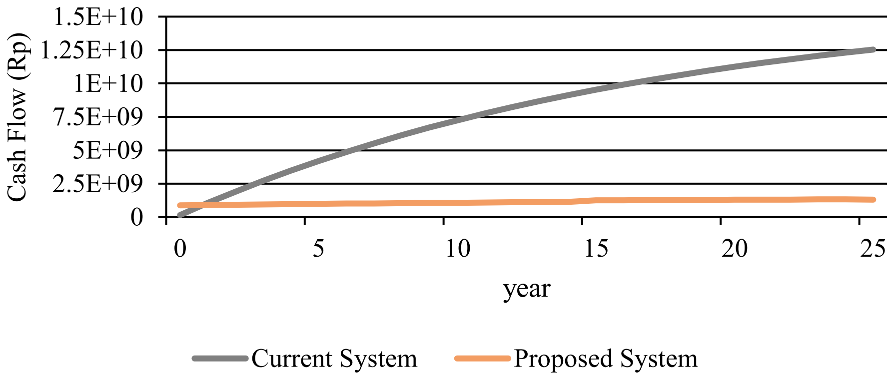
Based on simulation results using Homer Pro, all three rooftop PV system configurations On-Grid, Off-Grid, and Hybrid Grid-Tied are capable of meeting the building's energy demand. The on-grid system generates 166,208 kWh/year with a consumption of 163,798 kWh/year, resulting in a surplus of 2,410 kWh/year. The Off-Grid system produces 123,361 kWh/year with a consumption of 85,228 kWh/year, yielding a significantly larger surplus of 38,133 kWh/year, which is stored in batteries for backup supply. Meanwhile, the Hybrid Grid-Tied system generates 140,699 kWh/year with a consumption of 135,537 kWh/year, providing a surplus of 5,162 kWh/year. Overall, all systems are capable of supplying the required load with varying levels of energy surplus. The Off-Grid system provides the largest energy reserve to ensure supply continuity without reliance on the utility Grid, while the On-Grid and Hybrid Grid-Tied systems demonstrate efficient performance with moderate surplus energy, maintaining system reliability effectively.

2. **Simulation Results and Techno-Economic Graphs**

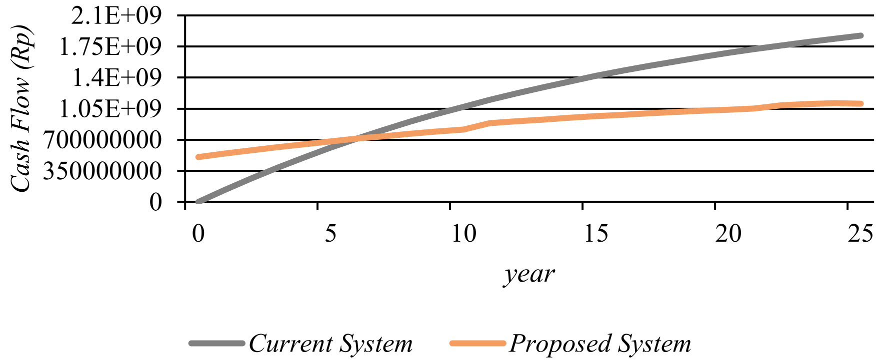
Based on the results of the Homer Pro simulation, the author obtained the cumulative cash flow graph results which can be seen in **Figure 5** below.



(a)



(b)



(c)

Figure 5. Simulation Results Graph (a) On-Grid System, (b) Off-Grid System, (c) Hybrid Grid-Tied System

Based on a cumulative cash flow analysis over the 25 year project life, all proposed systems demonstrate superior economic performance compared to the existing system. In the On-Grid system scenario in **Figure 5 (a)**, the proposed system requires an initial investment of IDR 393 million, with a break-even point of 6.43 years (6 years and 5 months). After this period, the system provides greater savings with an NPV of IDR 398 million and an IRR of 15.1%, thus being declared economically feasible. In **Figure 5 (b)**, the Off-Grid system, the initial investment is IDR 729 million, with a much faster payback period of approximately 9 months and 12 days, resulting in annualized savings of IDR

924 million, an NPV of IDR 11.2 billion, and an IRR of 128%, indicating a very high level of economic feasibility. Meanwhile, in **Figure 5 (c)**, the Hybrid Grid-Tied system has an initial investment of IDR 505 million with a payback period of 4.91 years (4 years 11 months), resulting in an NPV of IDR 766 million and an IRR of 19.6%.

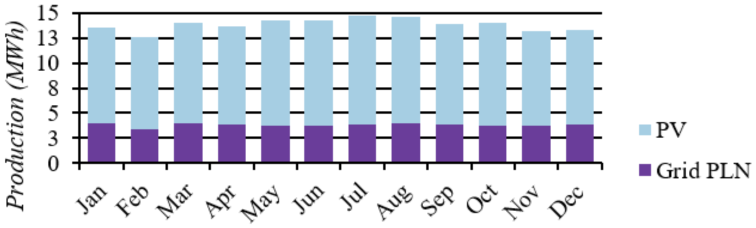
Because this building already has an existing generator, the author conducted another simulation, which showed that its impact on economic parameters was relatively small. The generator only operates for approximately 142 hours per year with an energy production of 2,848 kWh/year, thus its role is limited as a backup source. Therefore, the overall economic performance of the system remains dominated by the contribution of the solar power plant and batteries. For clearer results, please see **Table 7** below.

Table 7. Techno-Economic Comparison of Rooftop PV System Configurations

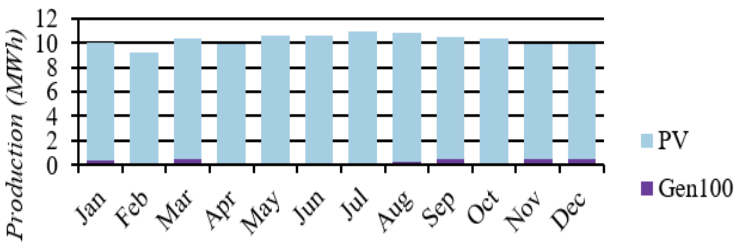
Parameter Ekonomi	**Nilai**		
	On-Grid System	**Off-Grid System**	**Hybrid Grid-Tied System**
Capital Investment	Rp 393 M	Rp 729 M	Rp 505 M
Simple payback	6,43 Yr (6 yr, 5 month)	9 month 12 days	4,91 Yr (4 yr 11 month)
Net Present Value	Rp 398 M	Rp 11,2 B	Rp 766 M
Return on Investment	11,6 %	123%	15,4 %
Internal Rate of Return	15,1 %	128%	19,6 %
Discounted Payback Period	8,32 Yr (8 yr, 4 month)	10 month	6 Yr, 9 month
Net Present Cost	Rp 1,47 B	Rp 1,31 B	Rp 1,11 B
LCOE	Rp 696,46	Rp 1,192.76	Rp 631,58
Operation & Maintenance	Rp 83,7 M	Rp 33,64 M	Rp 56,5 M
Annualized Savings	Rp 61,2 M	Rp 924 M	98,3 M

3. Electric Energy Production

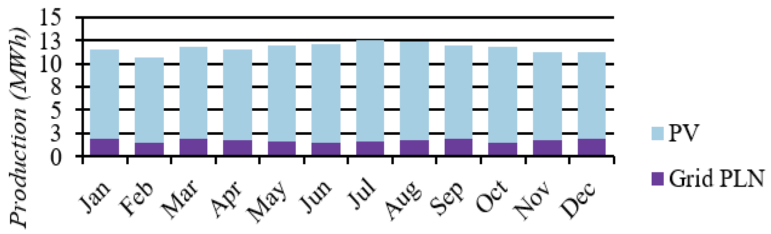
Based on the simulation results, the author obtained a production yield graph, which can be seen in **Figure 6** below. This analysis aims to determine the contribution of each energy source and the level of dependence on external electricity sources.



(a)



(b)



(c)

Figure 6. Electric results graph (a) On-Grid System, (b) On-Grid System, (c) Hybrid Grid-Tied System

Based on the analysis results, the On-Grid system produces approximately ±13–15 MWh per month, with PV as the dominant source, while still relying on the utility grid with relatively constant contribution. This indicates that the system effectively reduces grid consumption but is not fully independent. In contrast, the off-grid system generates around ±9–11 MWh per month, supplied entirely by PV with a generator as backup, where the generator contribution is minimal. This reflects a high level of energy independence, although the system has limitations in capacity and flexibility.

The Hybrid Grid-Tied system produces approximately ±12–14 MWh per month, with PV as the primary source supported by the grid and battery storage. The grid contribution is lower than in the On-Grid system, indicating improved utilization of solar energy and reduced dependency on the grid. This configuration offers a balanced performance in terms of energy independence, flexibility, and system reliability.

4. Efficiency Evaluation and Recommendations for Selecting a Solar Power Plant System

Based on the simulation results that have been carried out using Homer Pro, the evaluation of system efficiency is carried out by comparing the energy performance and techno-economic aspects of three system configurations, namely On-Grid, Off-Grid, and Hybrid Grid-Tied, which can be seen below.

1. The On-Grid system has a lower initial investment of Rp393 million, with an NPV of Rp398 million, an IRR of 15.1%, and a payback period of 6.43 years. This system is relatively stable and simple to operate, but still relies on the National Electricity Company grid, so the level of energy independence is still low.
2. The Off-Grid Rooftop Solar Power System demonstrated the highest economic performance with an NPV of Rp11.2 billion and an IRR of 128%, as well as a very fast payback period of approximately 9 months and 12 days. However, this high value needs to be analyzed critically because although this system provides very significant operational cost savings, its initial investment requirement is also the highest compared to other system configurations, namely Rp729 million. In addition, the Off-Grid system has a fairly high dependence on batteries and generators, which in its implementation require significant replacement and maintenance costs. On the other hand, this system also has limitations in operational flexibility because it is not connected to the National Electricity Company grid, so the entire continuity of electricity supply is highly dependent on PV performance, battery capacity, and generator backup sources.
3. The Hybrid Grid-Tied system demonstrated fairly balanced performance, with an investment value of Rp505 million, an NPV of Rp766 million, an IRR of 19.6%, and a payback period of 4.91 years. This system is able to optimize solar energy use with battery support while maintaining access to the National Electricity Company grid, thereby increasing system reliability and flexibility.

Based on the evaluation results, the Hybrid Grid-Tied system can be recommended as the most optimal choice. This is because this system is able to achieve a balance between energy efficiency and economic feasibility, with a level of energy surplus that is not excessive, lower dependence on National Electricity Company. compared to On-Grid systems, and higher operational flexibility compared to Off-Grid systems. In addition, this system also provides a relatively fast return on investment with more controlled operational risks. Thus, the selection of the Hybrid Grid-Tied rooftop solar system is considered the most efficient and reliable solution to be implemented, especially in buildings that are still connected to the National Electricity Company grid but desire a higher level of energy independence and long-term cost efficiency.

IV. Conclusion

Based on the research objective of designing and analyzing the performance and techno-economic feasibility of rooftop photovoltaic (PV) systems for the operational building of Perum Jasa Tirta I WS Brantas Division, simulation results using Homer Pro indicate that all three configurations are capable of meeting the building energy demand of 233.5 kWh/day or 85,192.10 kWh/year. The On-Grid system generated 166,208 kWh/year with a Capital Investment of IDR 393 million, Net Present Value (NPV) of IDR 398 million, Return on Investment (ROI) of 11.6%, Internal Rate of Return (IRR) of 15.1%, and a Levelized Cost of Energy (LCOE) of IDR 696.46/kWh, with a simple payback period of 6.43 years. However, this system still depends on the utility grid. The Off-Grid system produced 123,361 kWh/year with the highest economic indicators, including an NPV of IDR 11.2 billion, ROI of 123%, IRR of 128%, and a payback period of approximately 9 months and 12 days. Nevertheless, this configuration requires the highest initial investment of IDR 729 million, has strong dependence on battery storage and backup generators, and results in the highest LCOE value of IDR 1,192.76/kWh. Meanwhile, the Hybrid Grid-Tied system generated 140,699 kWh/year with a Capital Investment of IDR 505 million, NPV of IDR 766 million, ROI of 15.4%, IRR of 19.6%, and an LCOE of IDR 631.58/kWh, with a payback period of 4.91 years. In addition, this system has the lowest Net Present Cost of IDR 1.11 billion and Annualized Savings of IDR 98.3 million per year.

Based on the overall technical and techno-economic evaluation, the Hybrid Grid-Tied system is recommended as the most optimal configuration because it provides a balance between energy production and consumption, economic efficiency, operational flexibility, and system reliability. This system has lower dependence on the utility grid compared to the On-Grid system and does not require excessive battery capacity like the Off-Grid system. Therefore, the Hybrid Grid-Tied system is considered the most suitable solution for operational buildings requiring reliable energy continuity and long-term cost efficiency. Future research can be further developed by considering dynamic load variations, optimization of PV and battery capacities, and integration of more efficient energy storage technologies to enhance system sustainability and reliability.

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