Study of Smart Microgrid Technology on a Laboratory Scale Grid System

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Abstract - The utilization of renewable energy sources to meet electricity demand has become increasingly important. However, comparative studies on the technical and economic performance of on-grid and off-grid smart microgrid systems remain limited. This study aims to evaluate the configuration and performance of a smart microgrid system by comparing different operating configurations using HOMER software. The system was modeled by defining the electrical load, simulating the proposed configurations, and evaluating their technical and economic performance based on power output, Net Present Cost (NPC), and Cost of Energy (COE). The results show that the proposed grid-connected smart microgrid provides the best overall performance, with approximately 80% of the electrical energy demand supplied by the photovoltaic (PV) system and the remaining 20% provided by the PLN grid, demonstrating effective utilization of renewable energy resources. Economically, the proposed system achieves an NPC of Rp. 828,391,700 and a COE of Rp. 419.28, which are lower than those of the off-grid configuration (NPC of Rp. 2,664,679,000 and COE of Rp. 3,151.07) and the grid-only configuration (NPC of Rp. 906,104,800 and COE of Rp. 1,071.00). These findings indicate that integrating photovoltaic generation with the utility grid offers a more cost-effective and reliable solution while significantly increasing the contribution of renewable energy to the electricity supply. Therefore, the proposed smart microgrid configuration can serve as a practical reference for the design and economic evaluation of future grid-connected renewable energy systems.

Keywords — Renewable Energy, On Grid System, Off Grid System, Efficient.

I. Introduction

The increasing demand for electrical energy, accompanied by global commitments toward decarbonization and sustainable development, has accelerated the transition from conventional fossil-fuel-based power generation to renewable energy sources. Many countries, including Indonesia, are actively promoting the integration of renewable energy technologies into their electricity sectors to reduce greenhouse gas emissions and improve energy security [1]. However, the geographical characteristics of Indonesia as an archipelagic country create significant challenges in providing reliable electricity access to remote islands and isolated regions. In many locations, extending the main grid is technically difficult and economically expensive, making decentralized energy systems a more feasible solution. Hybrid power generation systems that combine solar photovoltaic, wind energy, diesel generators, and battery energy storage have emerged as promising alternatives for supplying electricity in off-grid and weak-grid areas [2]. Furthermore, the development of sustainable energy technologies has become a strategic component in supporting Indonesia’s long-term energy transition agenda and national energy resilience [3]. Technological advancement in the energy sector also plays an important role in improving electricity accessibility while ensuring environmental sustainability and operational efficiency [4]. Despite these developments, determining the most appropriate smart microgrid configuration that simultaneously provides reliable operation and economic feasibility remains a significant challenge, particularly for distributed power systems operating under varying load conditions. Therefore, research on distributed energy systems capable of operating independently and efficiently is becoming increasingly important to support the realization of reliable and sustainable electricity infrastructure.

One of the major challenges in renewable energy utilization is the intermittent and variable nature of renewable resources. Solar photovoltaic systems depend on solar irradiance conditions, while wind power generation relies heavily on wind speed variations, causing fluctuations in power output throughout the day [5]. Such uncertainty can negatively affect system stability, power quality, and reliability if not managed appropriately. To overcome these limitations, energy storage technologies and advanced energy management systems are required to balance generation and consumption in real time [6]. Battery Energy Storage Systems (BESS) have been widely adopted to mitigate renewable energy intermittency by storing excess energy during periods of high generation and supplying energy when generation decreases [7]. In addition, the integration of distributed energy resources into modern power networks requires intelligent control mechanisms capable of coordinating multiple generation sources and loads efficiently [8]. Previous studies have shown that the combination of renewable energy generation, battery storage, and advanced control systems can significantly improve system reliability and reduce dependence on fossil-fuel-based generation [9]. However, most previous studies have focused on component integration or energy management strategies, while comparative evaluations of on-grid and off-grid smart microgrid configurations under identical load conditions remain limited. This study addresses this gap by comparatively evaluating the technical and economic performance of both configurations using HOMER simulation, providing a practical reference for selecting the most suitable smart microgrid configuration based on system performance and cost.

The smart microgrid concept has emerged as one of the most promising solutions for addressing the technical challenges associated with renewable energy integration. A smart microgrid is a localized electrical network that combines distributed generation units, energy storage systems, loads, and intelligent control strategies to operate either in grid-connected or islanded mode [10]. Through advanced monitoring, communication, and automation technologies, smart microgrids can optimize power flow, improve energy efficiency, and enhance supply reliability under varying operating conditions [11]. Several studies have demonstrated the effectiveness of smart microgrid systems in supporting rural electrification programs, community energy systems, and isolated island power networks [12]. In addition, smart microgrids offer economic and environmental benefits by maximizing renewable energy utilization and minimizing the operational costs associated with conventional generators [13]. The flexibility of microgrid architecture also enables better adaptation to future increases in electricity demand and the integration of additional renewable energy resources. As electricity systems continue to evolve toward decentralized and digitalized structures, smart microgrids are increasingly recognized as a strategic technology for achieving sustainable and resilient energy systems [14]. Therefore, understanding the operational characteristics and performance of smart microgrid systems has become an essential area of research in modern electrical power engineering.

Numerous studies have investigated the planning, optimization, and implementation of microgrid systems using various renewable energy configurations. Khamharnphol et al. developed a hybrid solar, wind, diesel, and battery system optimized using HOMER Pro and demonstrated its capability to improve energy reliability while reducing operational costs [14]. Similar findings were reported in studies examining renewable energy planning for coastal and remote areas, where hybrid microgrids provided economically viable solutions for electricity generation [15], [16]. Research on photovoltaic power plants in small islands also highlighted the importance of integrating renewable energy with energy storage systems to ensure supply continuity [17]. Moreover, recent investigations into distributed energy resource integration have emphasized the role of advanced control and optimization methods in enhancing system performance and reliability [18]. Despite these developments, most existing studies focus primarily on simulation-based optimization or large-scale implementation scenarios. Limited attention has been given to laboratory-scale smart microgrid systems that can serve as experimental platforms for validating operational behavior, energy management strategies, and system responses under varying load conditions. Consequently, there remains a need for empirical investigations that bridge the gap between theoretical simulations and practical implementation through controlled laboratory-scale experimentation.

At Institut Teknologi PLN, efforts to develop smart microgrid technology have previously been initiated through research conducted by Suyanto and Hariyanto, which focused on measuring renewable energy potential and analyzing load profiles to assess technical feasibility [19]. While the study successfully provided valuable insights into the development of smart microgrid systems, further investigation is required to evaluate system performance under dynamic operating conditions and varying load demands. In addition, the increasing complexity of modern power systems necessitates more comprehensive analyses that incorporate energy optimization, load management, and operational efficiency considerations. Existing literature has highlighted the importance of intelligent energy management strategies for maintaining system stability and maximizing renewable energy penetration [10]. However, there is still limited experimental evidence regarding how laboratory-scale smart microgrid configurations perform when subjected to different load scenarios and operational constraints. This limitation creates a research gap that must be addressed to improve the understanding of practical smart microgrid implementation and to support future large-scale deployment. Therefore, laboratory-based performance evaluation becomes essential to validate theoretical assumptions and provide practical recommendations for microgrid development.

Although previous studies have demonstrated the benefits of renewable energy integration, battery energy storage, and energy management systems in improving microgrid performance, limited research has comprehensively compared the technical and economic performance of on-grid and off-grid smart microgrid configurations under the same load conditions using actual laboratory load data. Moreover, few studies have combined simulation-based optimization with validation based on real operating conditions to provide practical guidance for selecting the most suitable microgrid configuration. Therefore, this study addresses these gaps by evaluating and comparing both configurations through HOMER simulation using a laboratory-scale smart microgrid system.

Based on the aforementioned background, this study aims to investigate the implementation of smart microgrid technology on a laboratory-scale grid system at Institut Teknologi PLN. Specifically, the research seeks to determine the configuration of the smart microgrid system, analyze the influence of load variations on generated output power, and evaluate the overall performance of the smart microgrid under different operating conditions. Furthermore, this study performs an analysis of optimization results generated through simulation and compares them with actual laboratory observations to obtain a comprehensive understanding of system behavior. The novelty of this research lies in the integration of experimental laboratory-scale testing with performance evaluation and optimization analysis, providing practical insights beyond purely simulation-based approaches. The findings are expected to contribute to the development of reliable and efficient smart microgrid systems that can support renewable energy integration in remote areas, isolated islands, and future decentralized electricity networks [14]. In addition, the results may serve as a reference for researchers, policymakers, and utility companies in designing sustainable energy systems that align with national energy transition objectives and long-term electricity sector development strategies [20], [21].

II. Research Method

This research begins by implementing several methods, namely by collecting data used for the study, which uses loading data from the Institut Teknologi PLN renewable energy laboratory, as well as searching for several references from reading sources, namely journals, relevant previous studies, or reading books related to the discussion of smart microgrid systems.

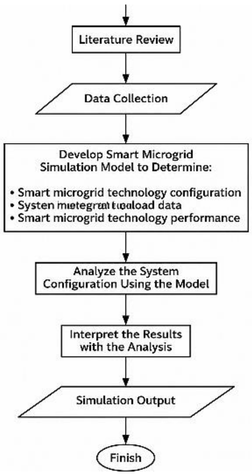

Figure 1 Research Design Flowchart

A. *System Single Line Diagram*

This study uses several components or equipment corresponding to those in the ITPLN renewable laboratory with the same type and capacity. These tools will be arranged into a system in the simulation that will be used to determine several parameters previously mentioned in the introduction.

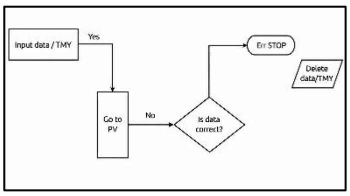

Figure 2 Single Line Diagram of On-Grid System

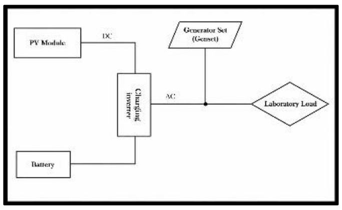

Figure 3 Single Line Diagram of Off-Grid System

B. *Simulation Design*

The simulation was designed to evaluate the configuration, power output, and performance of the proposed smart microgrid system under both on-grid and off-grid operating conditions using HOMER software. The simulation model was developed based on the components of the existing system, including the photovoltaic (PV) array, inverter, utility grid, battery storage, and load profile. The on-grid and off-grid configurations were then simulated to analyze their technical and economic performance under the same operating conditions.

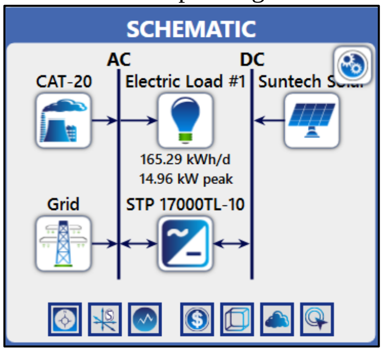

Figure 4 Single Line Diagram of HOMER On-Grid System

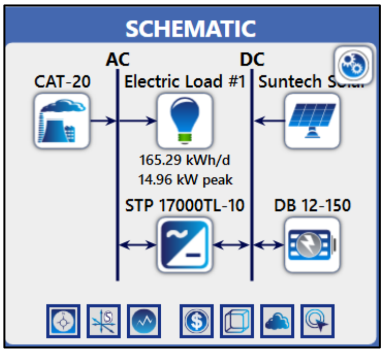

Figure 5 Single Line Diagram of HOMER Off-Grid System

C. *Data Collection and Data Processing Techniques*

The method is carried out by collecting data used for the research, which uses loading data from the ITPLN renewable energy laboratory, as well as searching for several references from reading sources, namely journals, relevant previous studies, or reading books related to the discussion of smart microgrid systems [8], [9]. Furthermore, the analysis method is carried out by creating a simulation or designing the system using engineering software, namely HOMER Pro, to perform analysis on the system that has been created [10]. Once the simulation is performed, the results of the power output or total energy production generated, system configuration, and the costs required to build the system can be determined. By using several equations below [11].

Cross-Sectional Area of Solar Panels

$$A = P \times L \qquad (1)$$

Where:
A = Surface area of the panel (m^2)
P = Length of the solar cell
L = Width of the solar cell

Received Power (Input Power)

Pin = Ir x A (2)

Where:
Pin = input power due to solar irradiation (watt)
Ir = solar irradiation level (Watt/m^2)
A = surface area of the solar cell (m^2)

Total Load in Watt Hour (Wh)
Determining the daily calculation of the total load used in the daily total load is made based on the electrical load.[12]

EB = Wtot x duration of PLTS usage (3)

Where:
EB = total load
Wtot = reactive power (W)

Distributed System Load

EA = 33.3% x EB (4)

Where:
EA = system load (Wh)
EB = total load (Wh)

Assumption of Losses
The loss value in the system is assumed to be 15%, because all components of the system used are still new. [3]
The total of the overall energy (ET) of the system can be described in the equation:

ET = EA + system losses
ET = EA + (15% x EA) (5)

Where:
ET = total energy consumption
EA = system load

Net Present Cost (NPC)
Net Present Cost is the total cost of requirements that will be used to build a project or implement components in terms of installation and at the time of operating the project [13].
NPC = Capital Cost + Replacement Cost + O&M Cost – Salvage (6)
Where:
Capital Cost = component cost
Replacement Cost = component replacement cost
O&M Cost = operational and maintenance cost
Salvage = remaining cost of the component

Cost of Energy (COE)
Cost of energy can be defined as a cost to obtain electrical energy in units per 1 kWh. This COE can be found by dividing the annual cost by the annual energy production generated by the power plant. To obtain the COE (Cost of Energy) value, the following equation is used [14]
TAC (total annualized cost) = total annual cost of the power generation system
Total annual energy for kWh load

Total Energy Production
The total energy released when the components are operating can be determined by the following equation.
Where:
Total energy production (kWh)
Total energy production of photovoltaic (kWh)
Total energy production of PLN grid (kWh)

Renewable Penetration
Renewable Penetration is the renewable energy summed up from the total energy used, this energy is produced by the system, namely the renewable energy system (RES), the renewable penetration value can be determined by the following equation.[15]
Where:
Amount of electrical energy released by the renewable energy system (kWh)
Amount of electrical energy released by the system power plant (kWh)

III. Results and Discussion

A. Electrical Load Profile
This load profile represents the load capacity required to distribute energy within a room on a daily basis. From the existing electrical load data, the load data can be obtained by forming a pattern in the electrical load as shown in the table and figure below.

Table 1 Real Load Profile of the Laboratory

Time (Hour)	Load (kW)	Time (Hour)	Load (W)
00.00	3,885	12.00	7,929
01.00	3,978	13.00	6,998
02.00	4,844	14.00	7,002
03.00	4,948	15.00	6,976
04.00	4,860	16.00	6,591
05.00	5,666	17.00	5,896
06.00	5,986	18.00	5,950
07.00	5,947	19.00	5,922
08.00	5,979	20.00	5,598
09.00	6,996	21.00	5,876
10.00	6,894	22.00	4,991
11.00	7,340	23.00	3,998

From the data presented in Table 1, the 24-hour daily load profile was established as the input for the HOMER simulation. The load varies throughout the day according to laboratory activities and the operation of electrical equipment. The minimum load of 3.885 kW occurs at 00:00, when laboratory activities are minimal and only essential electrical equipment remains in operation. As laboratory activities begin in the morning, the load gradually increases and reaches its peak value of 7.929 kW at 12:00 due to the simultaneous operation of laboratory equipment, lighting, and air-conditioning systems. At 13:00, the load decreases slightly to 6.998 kW, which can be attributed to the completion of several laboratory activities and the temporary shutdown of some electrical equipment during the lunch break or transition between laboratory sessions. From 17:00 to 21:00, the load remains relatively stable at approximately 5.6–5.9 kW because laboratory activities have largely ended, leaving only essential equipment, security lighting, air-conditioning in selected areas, and other continuous base loads in operation. These variations represent the actual operating conditions of the laboratory and were used as the load profile for the HOMER simulation.

B. Solar Irradiation

Then, Table 2 shows the output value of solar energy or radiation in the environment of the PLTS laboratory building within a five-day period based on NASA observations, along with the graph of the solar irradiation data [16], [17]. The following table displays varying solar irradiation emissions from 07.00 to 18.00.

Table 2 Daily Solar Irradiation

Time (Hour)	Day 1	Day 2	Day 3	Day 4	Day 5
07.00	30	100	50	30	120
08.00	60	340	40	70	260
09.00	130	470	100	90	620
10.00	290	600	160	80	900
11.00	600	940	100	120	950
12.00	850	1,110	10	100	930
13.00	880	1,140	80	150	940
14.00	700	1,050	160	20	990
15.00	760	850	20	90	810
16.00	420	550	40	90	650
17.00	70	320	20	60	420
18.00	70	100	10	20	110

Furthermore, the calculation of input power and output power of the PLTS is carried out by using the specifications of the PV used, with specifications resembling the simulation system above.
Suntech Solar Panel
With Specifications:
P = 1650 mm = 1.65 m
L = 992 mm = 0.92 m

$$A = P \times L$$
$$= 1{,}65\ m \times 0{,}92\ m$$
$$= 1{,}6368\ m^2$$

Input Power Due to Solar Irradiation

$$Pin = Ir \times A \tag{6}$$

Day 1

$Ir = 202{,}5\ W/m^2$
$Pin = 202{,}5\ W/m^2 \times 1{,}6368\ m^2$
$Pin = 331{,}452\ W$
Conducted within a 1-hour interval period

Table 3 Daily Input Power Calculation

Day	Ir (W/m2)	A (m2)	Pin (Watt)
1	202.5	1.636	19,887.12
2	315.417	1.636	30,976.47
3	32.916	1.636	3,232.68
4	38.333	1.636	3,764.63
5	320.833	1.636	31,508.36

In Table 3, the input power values are generated from the multiplication of the solar irradiation that can be captured daily by the area of the solar panels used, obtaining the input power values as shown above. The results on Day 3 and 4 obtain lower values than the others due to the solar irradiation value generated from the solar cells having a low value as well [18]. Because a low solar irradiation value will also produce low power.

C. PLTS Output Power

Average Output Load Each Day from Real-Time Monitoring Results

Obtaining the total daily energy consumption, namely in Table 3.4, with a loading duration of 24 hours.

Day 1

Total daily energy consumption = 318,290 W
Loading duration = 24 hours

$$Average\ Output\ Load = \frac{\text{Total daily energy consumption}}{\text{Loading duration}n} \text{ [19]}$$

$$Average\ Output\ Load = \frac{318.290}{24} = 13.262{,}08\ W$$

Table 4 Daily Average Load Calculation

Day	Energy Consumption (W)	Loading Duration	Average Load (W)
1	318,290	24 Hours	13,262.08
2	476,480	24 Hours	19,853.3
3	55,370	24 Hours	2,307.08
4	65,740	24 Hours	2,739.16
5	485,540	24 Hours	20,230.83

In Table 4, several discussions can be generated, namely that the amount of daily energy consumption produced varies according to the conditions of the parameters used for generation, such as the generated solar energy. Specifically, on Day 3 and 4, the daily energy consumption is lower and the average daily load value is also lower due to the less-than-optimal energy generation from sunlight, as several factors such as weather will yield lower results [20], [21].

Table 5 Daily PV Output Power

Time (Hour)	Day 1	Day 2	Day 3	Day 4	Day 5
07.00	2,330	6,740	3,850	1,940	7,470
08.00	4,490	21,940	3,160	4,850	17,730
09.00	9,390	30,990	6,810	6,630	39,550
10.00	20,290	39,610	11,470	6,010	56,300
11.00	40,030	58,630	6,760	8,740	59,500
12.00	54,060	68,270	770	6,890	58,680
13.00	55,860	69,650	5,330	10,730	59,210
14.00	45,570	65,100	11,150	1,220	61,870
15.00	48,510	53,340	1,210	6,400	51,120
16.00	28,010	35,290	2,530	6,490	40,930
17.00	4,670	20,670	1,580	4,410	26,270
18.00	5,080	6,250	750	1,430	6,910

Total Output of Solar Modules

Day 1

The highest load used is sourced from Table 5.

Total Load (EB)

Highest load = 55,860 W

Duration of PLTS usage = 12 hours

$$E_B = 55860\ W \times 12 hour$$
$$E_B = 670320\ Wh$$

Distributed system load:

EA = 33.3% × EB

$$E_A = 33{,}3\ \% \times 670320\ Wh$$
$$E_A = 223216{,}56\ Wh$$

Total of All Energy:

ET = EA + (15% × EA)

$$E_T = 223216{,}56\ Wh + (15\% \times 223216{,}56\ Wh)$$
$$E_T = 256699{,}044\ Wh$$

Table 6 Total Daily Energy Calculation

Day	EB (Wh)	EA (Wh)	ET (Wh)
1	670,320	223,216.56	256,699.04
2	835,800	278,321.4	320,069.61
3	137,640	45,834.12	52,709.23
4	128,760	42,877.08	49,308.64
5	742,440	247,232.52	284,317.39

In the discussion of Table 6, the values of total load, distributed system load, and the total of all energy generated each day can be produced. To find the total of the overall energy generated, it is added with the system losses assumed at 15%, which implies that the components used in assembling this system are still considered new components and system losses remain low. Furthermore, the total of all energy generated on Day 3 and 4 is lower than the others, which can be caused by the highest system load used on those days being lower due to less-than-optimal energy generation from sunlight, causing the resulting energy output to be low compared to other days.

D. Net Present Cost (NPC)

Table 7 Component Costs

Component	Capital Cost (Rp)	Replacement Cost (Rp)	O&M Cost (Rp)	Salvage (Rp)	Total (Rp)
Inverter	68,642,222.22	0	28,311,702.95	0	96,953,925.17
Grid	0	0	-541,960,675.4	0	-541,960,675.4
Photovoltaic	678,616,352.2	0	594,782,131.3	0	1,273,398,483
System	747,258,574.4	0	81,133,158.86	0	828,391,733.3

In the table above, each component cost used to build the project is identified. The calculation can be performed by finding the NPC of the total requirements used by the system as follows.

E. Cost of Energy (COE)

Table 8 Energy Output and Costs

Evaluation Criteria	Value
Total Energy Serving Load (kWh/year)	140,889 kWh/year
Total Cost per Year (Rp)	Rp59,072,068.86

In the table above, each total energy used to satisfy the load and the total annual cost is identified. The calculation can be performed by finding the COE of the system as follows.

TAC = Rp 59,072,068.86

Eserved = 140,889 kWh/year

$$\text{COE} = \frac{59.072.068{,}86}{140.889} = Rp\ 419{,}28$$

F. Total Energy Production

Table 9 Energy Production

Component	Production (kWh)
Photovoltaic	117,113
PLN Grid	29,204

In the table above, each component production used to build the project is identified. The calculation can be performed by finding the Penergy from the total requirements used by the system as follows.

G. Renewable Penetration

Table 10 Renewable Penetration

Production	kWh/yr	%
Suntech 260S	117,113	80.0
Grid Purchases	29,204	20.0
Total	146,318	100

In the system output above, the energy production of each component used and the total of both system generations are respectively identified. The calculation can be performed by finding the renewable penetration from the total output generated by the system as follows.

H. Economic Value

Table 11 Economic Value Comparison of Systems

Parameter	On Grid PLN	Grid PLN	Off Grid
Total Energy Production (kWh/year)	146,318 kWh/year	60,330 kWh/year	134,666 kWh/year
Net Present Cost (Rp)	Rp828,391,700	Rp906,104,800	Rp2,664,679,000
Cost of Energy (Rp)	Rp419.28	Rp1,071.00	Rp3,151.07
Renewable Penetration (%)	83.1%	0.00%	100.00%

From the three respective system conditions, for a configuration that is more efficient in terms of initial cost or long-term cost savings for system construction, energy purchase per kWh, component construction or installation, as well as operations, the system in the first condition, on-grid renewable energy connected to the PLN network, requires an initial capital or net present cost of around Rp. 828,391,700 and possesses the smallest initial capital value compared to the other two system conditions. Furthermore, for the energy purchase value per 1 kWh, a value of Rp 419.28 per kWh is obtained, which is cheaper compared to the other network systems.

I. System Production Value

Table 12 Comparison of Total System Production

Component	Production (kWh)		
	On Grid PLN	Grid PLN	Off Grid
Photovoltaic	117,113	0	134,666
PLN Grid	29,204	60,330	0

Under the on-grid configuration, the system produces the highest annual energy output of 146,317 kWh. This is because the electrical load is supplied simultaneously by the photovoltaic (PV) system and the PLN grid, allowing the grid to compensate for periods of insufficient PV generation caused by variations in solar irradiation. As a result, the system can continuously satisfy the load demand while maximizing the utilization of available renewable energy, leading to higher overall annual energy production. In comparison, the grid-only configuration generates 60,330 kWh per year because the entire load is supplied exclusively by the PLN grid without any contribution from renewable energy sources. Meanwhile, the off-grid configuration produces 134,666 kWh annually, where the load is supplied solely by the PV system and battery storage. In this configuration, energy production is constrained by the available solar resource and the battery storage capacity, which limits the amount of energy that can be delivered during periods of low solar generation. These results indicate that integrating the PV system with the utility grid improves energy availability and system reliability while reducing dependence on a single energy source, making the on-grid configuration more suitable for sustainable and reliable electricity supply.

IV. Conclusion

Based on the results of this study, the following conclusions can be drawn:

1. The proposed smart microgrid system was successfully modeled and controlled using HOMER software. The system integrates a photovoltaic (PV) generation system with the utility grid and employs monocrystalline solar panels combined with a Sunny Tripower inverter, providing a reliable three-phase power conversion system.
2. The output power generated by the system varies according to load demand and photovoltaic generation. Lower average power output was observed on Days 3 and 4, which may be attributed to reduced solar energy absorption caused by less favorable solar irradiation conditions.
3. The performance of the smart microgrid system is reflected by its renewable energy penetration level. Under on-grid operation, approximately 80% of the electrical energy demand is supplied by the photovoltaic system, while the remaining 20% is provided by the PLN grid, indicating effective utilization of renewable energy resources.
4. The results demonstrate that the proposed smart microgrid configuration can support grid-connected renewable energy integration while maintaining system reliability and improving the contribution of renewable energy to the overall electricity supply.

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