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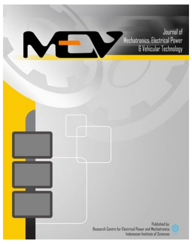

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Analysis of battery energy storage system (BESS) performance in reducing the impact of variable renewable energy generation intermittency on the electricity system

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Abstract

Indonesia has set a target to achieve a 23 % share of new and renewable energy (NRE) in its national energy mix by 2025. Sulawesi island has significant wind and solar energy potential, but the integration of these variable renewable energy (VRE) sources, such as solar photovoltaic (PV) and wind turbines (WT), poses challenges due to their fluctuating output. The aim of this study is to analyze the impact of battery energy storage systems (BESS) in reducing the intermittency of solar power generation and improving grid stability in North Sulawesi and Gorontalo. The study uses a combination of various technical simulations to assess the performance of BESS in stabilizing voltage and frequency fluctuations within the electricity system. The approach includes power flow analysis, transient stability testing, and short-circuit studies, with and without the integration of BESS. The results show that implementing a 10 MW/5 MWh BESS can significantly reduce frequency deviations, limiting frequency drops to 49.82 Hz during disturbances, compared to 49.67 Hz without BESS. In addition, BESS helps maintain voltage stability at critical substations by reducing voltage fluctuations by up to 40 %. This research demonstrates that BESS integration can enable a more stable and reliable grid, supporting the development of renewable energy without compromising power quality.

Keywords: BESS; battery storage; VRE intermittency; renewable energy; electricity system.

I. Introduction

Global climate change and energy crisis have driven the search for more sustainable energy alternatives. Renewable energy sources such as sunlight, wind, water, and biomass offer environmentally friendly and renewable solutions that can be continuously harnessed without depleting natural resources [1][2]. A key advantage of renewable energy is its ability to be utilized without causing significant environmental harm while also contributing to strengthening local economies at a lower cost than fossil fuels [3][4].

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However, renewable energy, such as solar photovoltaic (PV) and wind turbines (WT) face significant challenges, especially in terms of the variability of renewable energy (VRE) [5]. This variability can cause fluctuations in electricity supply, potentially resulting in blackouts or supply interruptions.

Previous research has explored various solutions to address VRE variability, including using a battery energy storage system (BESS) [6][7][8]. BESS functions to store electricity when production exceeds consumption and release it when production decreases, helping to maintain grid balance [9]. Energy storage technologies such as lead-acid to lithium-ion batteries have been developed and widely used. For example, several studies showed that BESS could improve grid stability by providing fast power backup [10][11][12]. However, these solutions come with several challenges, such as high investment costs, limited battery lifespan, and intensive maintenance requirements which may hinder large-scale implementation and long-term sustainability.

This study aims to fill this gap by analyzing the performance of BESS in reducing the impact of intermittency in solar power plants in North Sulawesi and Gorontalo. This study offers a novel, in-depth analysis, including long-term operational data, which has yet to be addressed in previous studies. The results of this research are expected to serve as a reference for electricity system managers and policymakers in designing and implementing effective and efficient energy storage solutions to support the achievement of national renewable energy targets and improve the reliability of the electricity supply.

II. Materials and Methods

This study follows a structured methodology that integrates technical analysis and financial evaluation to assess the performance of battery energy storage systems (BESS) in reducing the intermittency of solar power generation in North Sulawesi and Gorontalo. The research methodology is divided into several phases, each designed to comprehensively address different aspects of BESS integration within the electricity grid.

A. Site selection and data collection: Likupang (North Sulawesi) and Isimu (Gorontalo)

The first phase of the research involved selecting two solar power plant (Pembangkit Listrik Tenaga Surya, abbreviated to PLTS) sites: Likupang (15 MW) in North Sulawesi and Isimu (10 MW) in Gorontalo. These sites were chosen based on their high solar irradiation potential and existing grid connections. Figure 1 presents the locations of the Likupang and Isimu solar power plants. Operational data from both

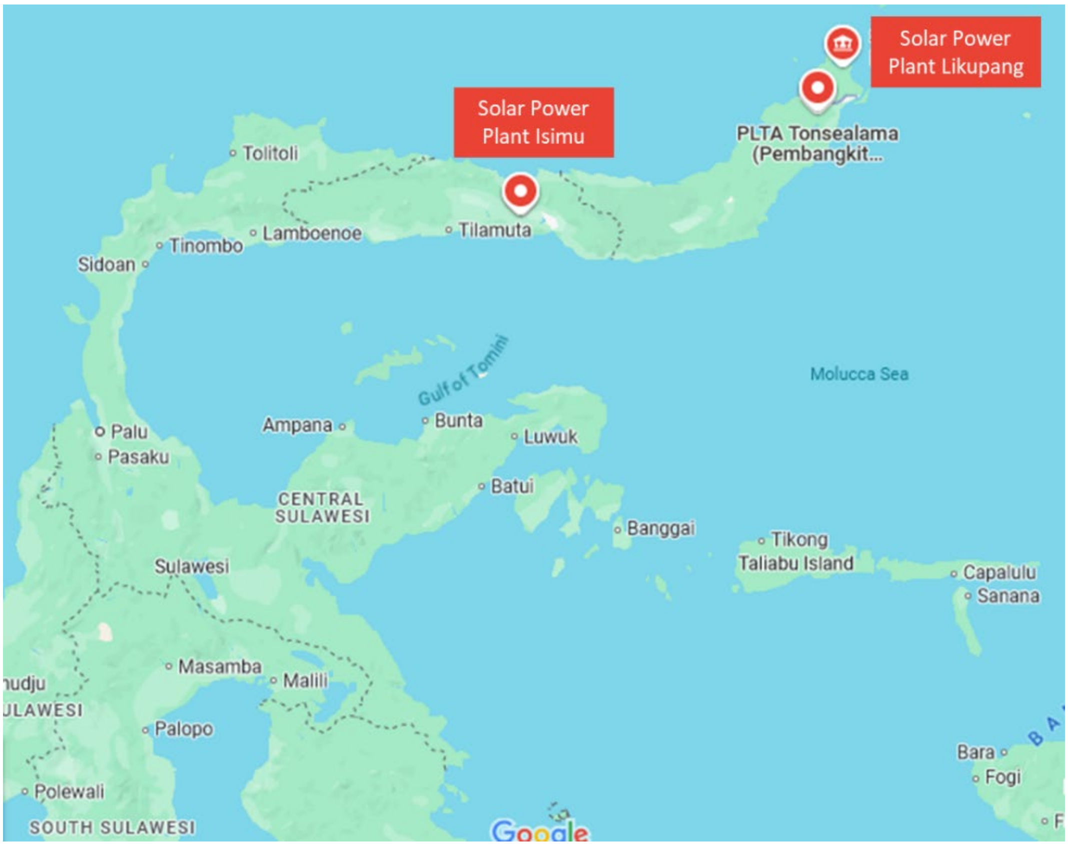


Figure 1. Location of the Likupang and Isimu solar power plants.

solar plants, including power output, load profiles, and system performance, were collected over a specified period. The data serves as the basis for analyzing the fluctuations in energy generation and assessing the impact of BESS on stabilizing the grid.

While the Likupang solar power plant (PLTS Likupang) contributes significantly to the analysis, the Isimu solar power plant (PLTS Isimu) also plays a crucial role in this study, particularly in demonstrating the combined effects of integrating multiple variable renewable energy (VRE) sources into the SulutGo electricity grid. PLTS Isimu, with a capacity of 10 MW, complements the 15 MW from Likupang, creating a larger VRE base that can influence grid performance and stability. Isimu complements Likupang's output, providing insights into how the variability from two solar plants affects grid stability. Isimu also contributes to the short-circuit analysis and contingency analysis, helping in assessing the grid's ability to handle power variability from two VRE sources. This dual-plant analysis underscores the necessity of BESS for managing combined solar power inputs and ensuring grid reliability.

The SulutGo system encompasses the electrical grid serving the North Sulawesi and Gorontalo regions. This system integrates various energy sources, including the PLTS Likupang and PLTS Isimu. With a grid capacity of approximately ±560 MW, the SulutGo system plays a crucial role in managing intermittency from variable renewable energy sources, particularly solar plants that produce power fluctuations due to changing weather conditions. In this study, the SulutGo system is the focus for analyzing the impact of integrating a battery energy storage system (BESS) in stabilizing power fluctuations caused by the PLTS.

B. Technical analysis of power fluctuations

In this phase, detailed simulations were conducted to analyze the fluctuations in the power output of both solar plants. The variability in solar energy production, caused by changing weather conditions and sunlight intensity, was measured in real-time intervals. The power flow analysis was performed using software tools to simulate scenarios both before and after the integration of BESS. Special attention was given to how BESS helps mitigate sudden drops in solar output, stabilizing voltage and frequency within the grid. The technical evaluation also included contingency analysis under N-1 conditions, short-circuit analysis, and transient analysis to observe the system's behavior under different grid stress scenarios. This phase of the study aimed to demonstrate the effectiveness of BESS in improving the resilience of the power grid.

This study analyzes several technical parameters to assess the impact of power fluctuations from the PLTS Likupang and PLTS Isimu solar power plants and the role of the battery energy storage system (BESS) in stabilizing these fluctuations. One of the key parameters measured is system frequency (Hz) which monitors the stability of grid frequency during power fluctuations caused by the solar plants. Under normal conditions, the frequency remains around 50 Hz, but it can drop or rise due to sudden changes in power output from the plants.

Another important parameter is substation voltage (kV) which tracks voltage variations at the Likupang and Isimu substations during periods of power fluctuations. Maintaining stable voltage is crucial for ensuring consistent power quality for consumers. The study also collects real-time data on the power output from the PLTS Likupang and PLTS Isimu. PLTS Likupang, with a capacity of 15 MW, and PLTS Isimu, with a capacity of 10 MW, exhibit significant output variations influenced by daily weather conditions. These collected data are used in simulations to evaluate how BESS mitigates the impact of sudden drops in power output, such as those caused by cloud cover, and helps maintain stability in both frequency and voltage within the grid.

C. Battery applications in power systems

Lead-acid batteries are an established and commonly used battery technology in solar panel systems for domestic and industrial use [13]. The size of the battery is adjusted according to the need to provide optimal power when the solar panel is not generating electricity, such as at night or during cloudy weather. The choice of battery type and capacity is a crucial factor in determining the battery system for solar panels. Lead-acid batteries are available in two main types: ventilated and valve regulated lead-acids (VRLA) [14]. VRLA is generally preferred because it performs better and requires less maintenance than ventilated batteries.

In addition to lead-acid batteries, lithium-ion battery technology is also increasingly popularly used in power systems as it has advantages in terms of higher energy density, longer lifespan, and better efficiency [15]. Lithium-ion batteries convert chemical energy into electricity through redox reactions within the battery cells. In the context of power systems, a battery energy storage system (BESS) [16] that uses lithium-ion batteries consists of several key components: a battery pack as the energy source, a battery management system (BMS) that monitors voltage, depth of discharge, and temperature to extend battery life, an inverter to convert direct current (DC) to alternating current (AC), and a local controller to optimize BESS operations according to needs and applicable regulations [17]. Implementing this BESS is very helpful in overcoming fluctuations in the output power of the solar power plant, ensuring more stable and reliable electricity availability.

A BESS stores electrical energy when production exceeds consumption and releases it back into the grid when production drops. In this study, the BESS used has a capacity of 10 MW/5 MWh. The system includes several key components, such as battery pack, which stores energy chemically, and BMS, which monitors the voltage, depth of discharge, and temperature to prolong battery life. Additionally, the system contains an inverter that converts DC to AC for use in the power grid and a local controller that optimizes BESS operations according to grid requirements and applicable regulations.

D. Fluctuation of solar power output

Solar power plants are a popular solution for sustainable energy. It converts solar energy into electricity through solar panels that capture sunlight and convert it into electricity through a photovoltaic process [18]. Despite its many advantages, solar power plants have limitations when generating energy at night or in bad weather, often requiring support from other energy sources [19]. One of the best ways to reduce fluctuations in solar power output is to use a battery energy storage system (BESS), which consists of batteries that store excess energy. BESS is beneficial in regulating the energy produced by solar power plants and allows consumers to utilize it more efficiently [20]. The main components of BESS can be seen in Figure 2.

Figure 2 shows the various essential components of the BESS that work synergistically to store and manage energy distribution. With the BESS in place, fluctuations in output power from the solar farm can be minimized, ensuring a more stable electricity supply for consumers.

The solar power plants studied in this research are located in North Sulawesi and Gorontalo, namely the Likupang and Isimu solar power plants [21][22]. PLTS Likupang has an installation capacity of about 15 MWac ± 75 % and is built on about 252,000 square meters. Based on the feasibility study, the average solar irradiation rate at the site is about 1,998 kWh/m^2/year. The estimated annual electricity production from the plant is about 23,652,000 kWh/year. The electricity generated will be transmitted through a 0.2 km long 20 kV underground cable from the site to the existing 70 kV PLN Likupang substation. An example of the Likupang PLTS power output at 15 MWp can be seen in Figure 3, and PLTS Likupang load profile per 1 second can be seen in Figure 4.

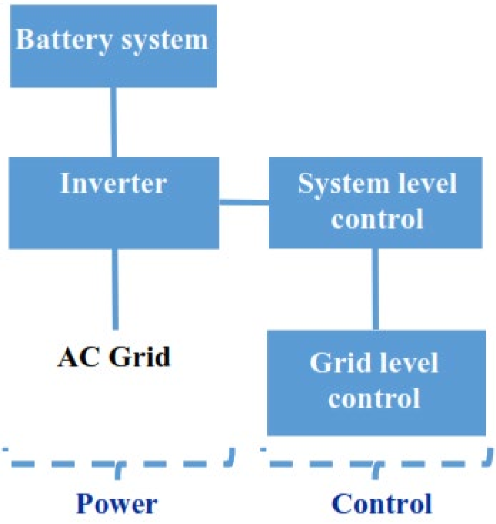


Figure 2. Main components of BESS.

Figure 4 shows the output power profile of the PLTS Likupang throughout the day, which shows the variation of energy production from morning to evening. This variation occurs due to changes in the intensity of sunlight received by the solar panels due to weather conditions.

The plant in Isimu, Gorontalo, has an installed capacity of about 10 MWac ±75 % and is built on about 100,000 square meters. Based on the feasibility study, the average solar irradiation rate at the site is about 1,890.7 kWh/m^2/year. The estimated annual production from the plant is about 21,500,000 kWh/year. The electricity generated will be transmitted through a 20 kV distribution network of approximately 114 km from the plant site to the 150 kV Isimu substation. A detailed description of the PLTS Isimu project and an example of the PLTS Isimu power output (10 MWp) can be seen in Figure 5 for the PLTS Isimu. Load Profile per 1 second can be seen in Figure 6.

Figure 6 illustrates how the output power of the PLTS Isimu solar farm varies throughout the day, showing a similar pattern to the Likupang solar farm but with different power peaks. These fluctuations illustrate the challenges faced in managing the power output of solar plants.

The output power graphs of Likupang solar PV and Isimu solar PV show the variation in energy production from the two solar power plants throughout the day. PLTS Likupang solar farm reaches peak power around 12:00 pm to 13:00 pm with a value close to 16 kW, while PLTS Isimu solar farm reaches peak power earlier

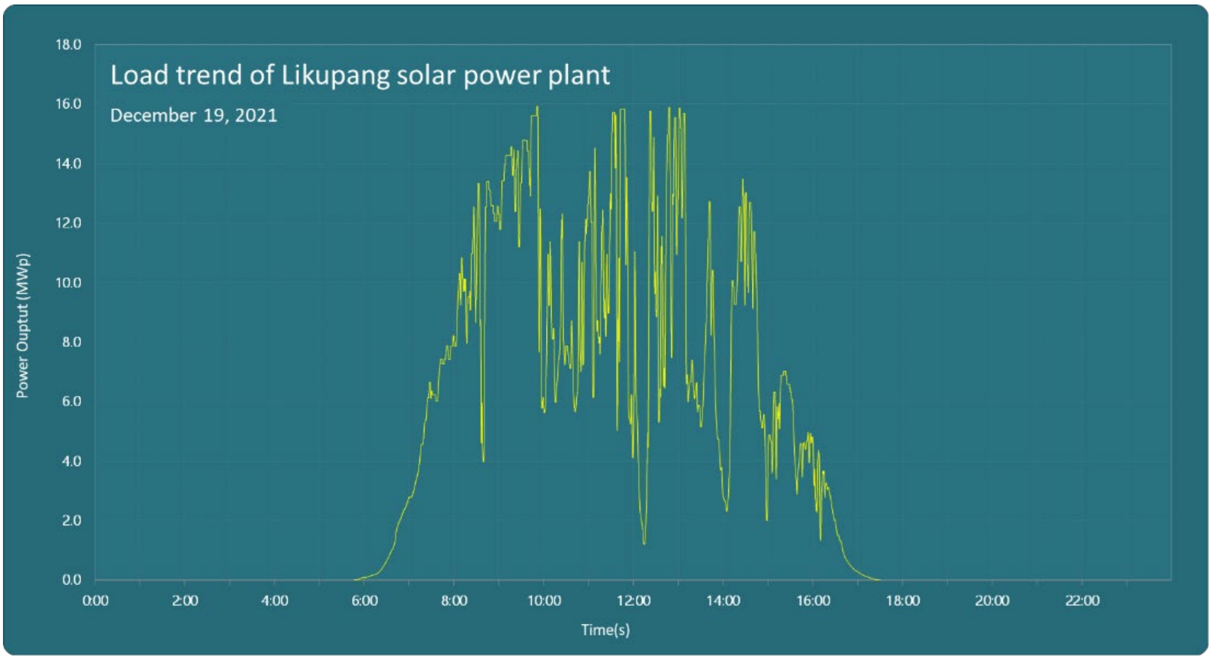


Figure 3. PLTS Likupang power output example (15 MWp).

between 8:00 am to 12:00 pm with a value close to 12 kW. Both plants show significant fluctuations in output power, but the fluctuations in the Likupang plant were more intense and frequent than the Isimu plant. After reaching the peak output power, PLTS Likupang solar farm remains volatile until late afternoon, while PLTS Isimu solar farm shows a more steady decline after the peak around noon. Both plants experience a significant drop in power after 3 pm, with the output power almost reaching zero at 5:30 pm, signaling that the sun already set. Sudden fluctuations in output power throughout the day, especially in the afternoon, are most likely caused by rapid changes in weather conditions or technical issues in the solar farm systems. A more in-depth analysis of weather data and the operational conditions of the solar farm could provide additional insights into the causes of the observed fluctuations as well as the overall performance of the system.

E. Utility-scale battery

Battery technology is undergoing rapid development today, with many companies from various industries, such as petrochemicals, electric cars, and renewable energy, competing to develop more efficient, durable, and economical batteries [23][24]. Utility-scale battery is a technology used to provide energy supply on a large scale and is directly connected

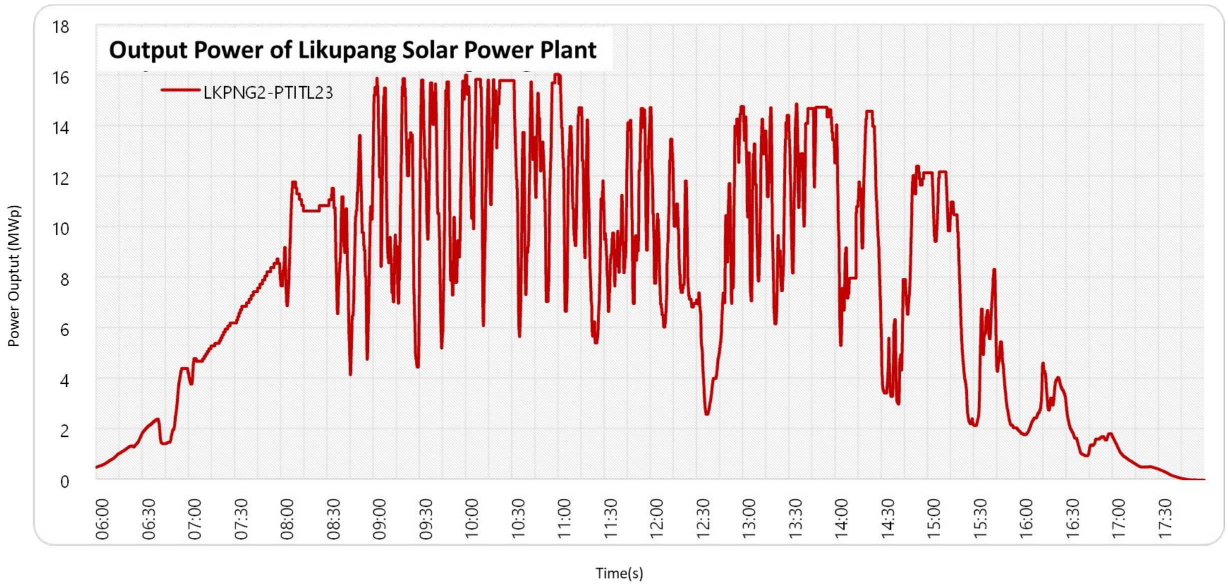


Figure 4. PLTS Likupang load profile per 1 second.

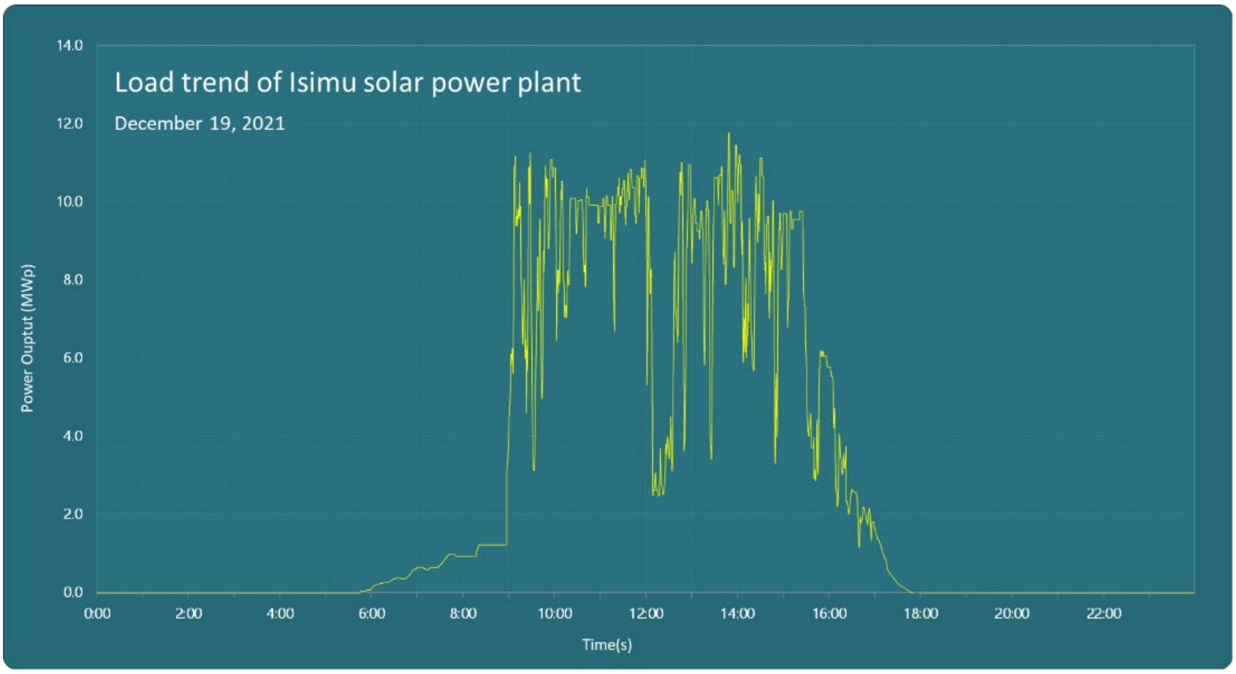


Figure 5. Power output example of PLTS Isimu (10 MWp).

to the primary power grid [25]. At first, batteries were only used in small electronic devices such as cell phones or laptops. However, with the development of technology, batteries have now been upgraded to store and provide greater power.

USB consists of a series of large batteries connected to the primary power grid and is typically used to store energy from renewable energy sources such as solar panels or wind turbines [26]. The main functions of USB include stabilization of the power grid, improvement of energy use efficiency, and reduction of energy costs [27]. In addition, USB can store energy when production exceeds consumption and release it when consumption exceeds production, thus it helps maintaining the power grid's balance and reliability. With these capabilities, USB plays a vital role in integrating more renewable energy sources into the power grid, supporting the achievement of renewable energy targets, and reducing dependence on fossil energy sources.

III. Results and Discussions

A. SulutGo system electricity condition

The SulutGo power system in 2023 consists of the North Sulawesi and Gorontalo electricity systems. The 2023 Annual Operating Plan notes the addition of PLTS Likupang with a capacity of 15 MW and PLTS

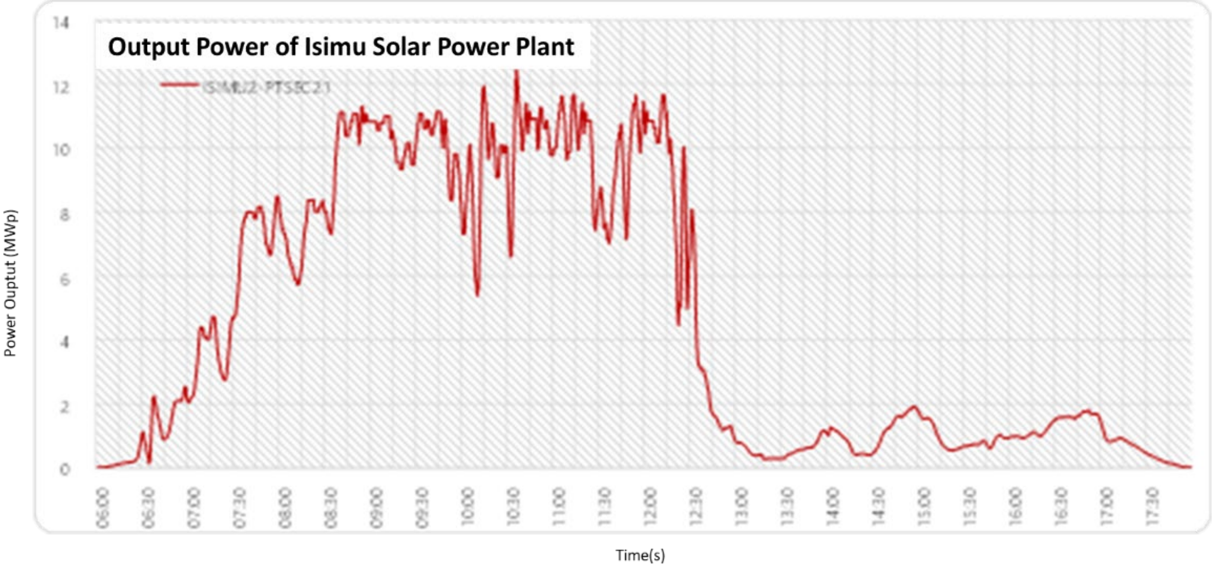


Figure 6. Load profile of PLTS Isimu per 1 second.

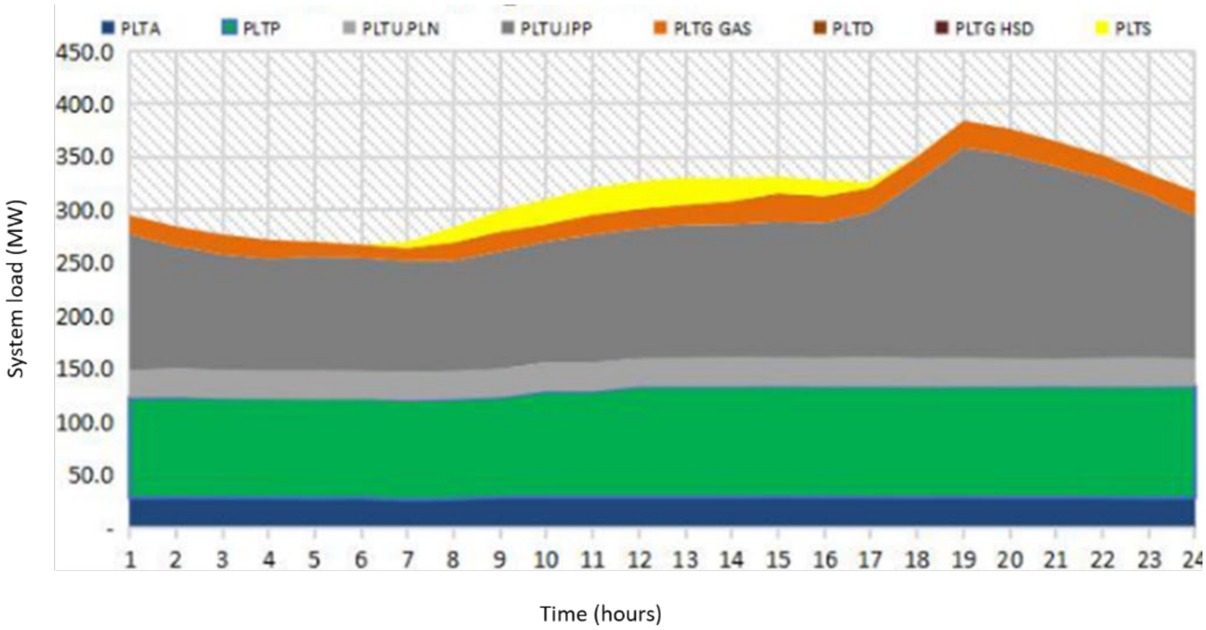


Figure 7. SulutGo system load stacking.

Isimu solar power plant with a capacity of 10 MW connected to the primary grid. Both plants are on-grid and have no energy storage. The monthly operation evaluation shows a system stiffness of 13 MW/Hz.

In addition to technical improvements, this study also considers the financial aspects of BESS implementation. The investment cost for a 10 MW/ 5 MWh BESS is approximately $5 million USD, covering installation, inverters, and battery management systems. Operational savings come from reduced reliance on fossil fuel generators and lower maintenance costs for conventional plants due to grid stabilization provided by BESS.

A cost-benefit analysis shows that the initial BESS investment can be recovered within 7 to 10 years through reduced fuel consumption and maintenance. Additionally, BESS improves grid reliability, minimizing potential financial losses from power outages or instability which contributes to long-term savings for utilities and the overall economy.

The capacity of the North Sulawesi and Gorontalo electricity network reaches about ±560 MW with a night peak load of about ±387 MW and a day peak load of about ±317 MW. In 2023, the estimated night peak load is about ±421 MW, and the day peak load is about ±346 MW. Various plants such as hydropower, mini hydro power plant (Pembangkit Listrik Tenaga Mini Hidro, abbreviated as PLTM), diesel power plant (Pembangkit Listrik Tenaga Diesel, abbreviated as PLTD), steam power plant (Pembangkit Listrik Tenaga Uap, abbreviated as PLTU), gas power plant (Pembangkit Listrik Tenaga Gas, abbreviated as PLTG), gas engine power plant (Pembangkit Listrik Tenaga Mesin Gas, abbreviated as PLTMG), geothermal power plant (Pembangkit Listrik Tenaga Panas Bumi, abbreviated as PLTP), and PLTS supply this system. Figure 7 shows the SulutGo System load stacking, which illustrates the contribution of various energy sources to the system load throughout the day.

B. Power flow profile

This section will discuss the impact of PLTS Likupang and PLTS Isimu on the SulutGo system. The scenario analyzed is at a low load time with a system load of 317 MW. The analysis includes several essential aspects.

First, a power flow analysis was carried out before and after the entry of the 15 MW PLTS Likupang and after the 10 MW PLTS Isimu entry. Second, a power flow analysis is carried out under N-1 contingency conditions on transmission lines directly connected to the interconnection point. Third, a short circuit analysis was carried out before and after PLTS Likupang and PLTS Isimu interconnection. Fourth, a transient analysis was carried out for the condition of the 15 MW PLTS Likupang and 10 MW PLTS Isimu. Finally, a battery requirement analysis is carried out to overcome the fluctuations of PLTS Likupang. The results of power flow under conditions before the interconnection of PLTS for the North Sulawesi and Gorontola systems are shown in Figure 8 and Figure 9.

Figure 8 depicts the power flow of the North Sulawesi system before the interconnection of the PLTS Likupang. Without solar generation, the system relies heavily on conventional power plants, and the power distribution is relatively stable but lacks significant renewable energy input. This figure sets the baseline for evaluating the impact of integrating (VRE) sources.

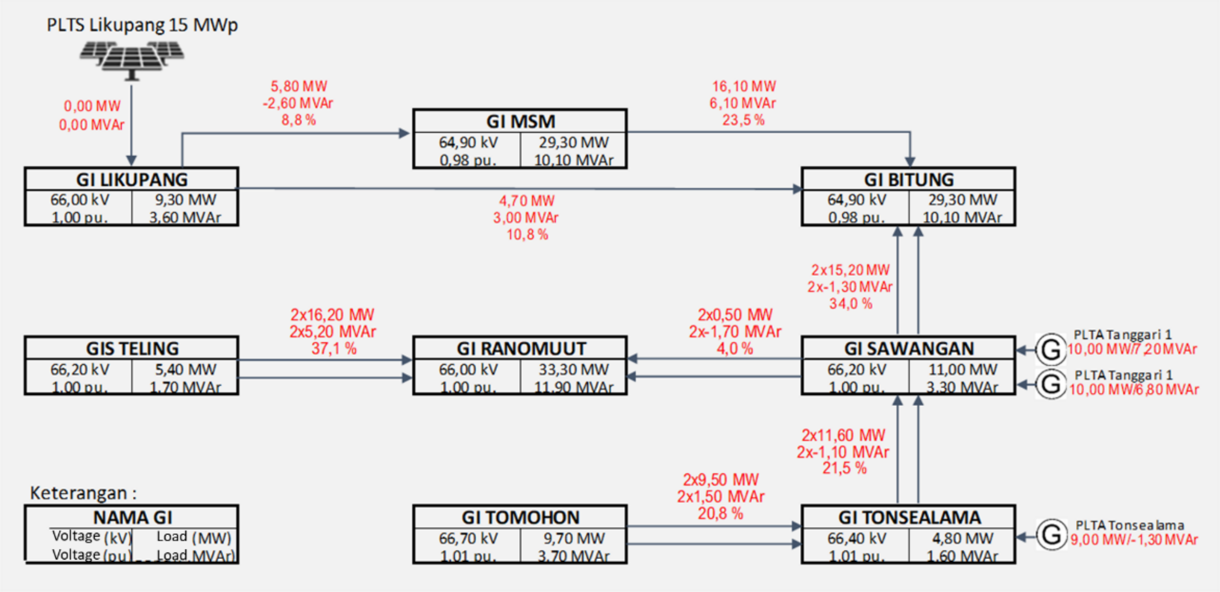


Figure 8. North Sulawesi system power flow before interconnection.

This diagram illustrates the distribution of electrical power through various substations (GI or GIS) in the region. PLTS Likupang solar farm contributes no power (0.00 MW) in this scenario. From GI Likupang, 9.30 MW of power flows with a reactive load of 3.60 MVAr to GI MSM with 5.80 MW of power flow and a reactive load of 2.60 MVAr. GI MSM then distributes 29.30 MW with a reactive load of 10.10 MVAr to GI Bitung, which has a voltage of 64.90 kV.

GI Bitung also receives power from GI MSM amounting to 4.70 MW with a reactive load of 3.00 MVAr. In addition, GI Bitung distributes power to GI Ranomuut and GI Sawangan. GI Ranomuut receives 20.60 MW and has a reactive load of 11.90 MVAr, while GI Sawangan receives 31.00 MW and a reactive load of 3.30 MVAr.

GI Ranomuut distributes power to GIS Teling with a 66.20 kV voltage of 5.40 MW and a reactive load of 1.70 MVAr. GI Sawangan distributes power to GI Teling, GI Tomohon, and GI Tonsealama. GI Tomohon receives 9.70 MW of energy with a reactive load of 5.70 MVAr, while GI Tonsealama receives 4.80 MW of power with a reactive load of 1.60 MVAr.

The hydropower plants connected to this network also affect the power flow. PLTA Tanggari 1 contributed 10.00 MW with a reactive load of 6.80 MVAr, PLTA Tanggari 2 contributed 10.00 MW with a reactive load of 8.80 MVAr, and PLTA Tonsealama contributed 9.00 MW with a reactive load of 1.30 MVAr.

Overall, the diagram in Figure 8 depicts the energy flow in the North Sulawesi power system without the

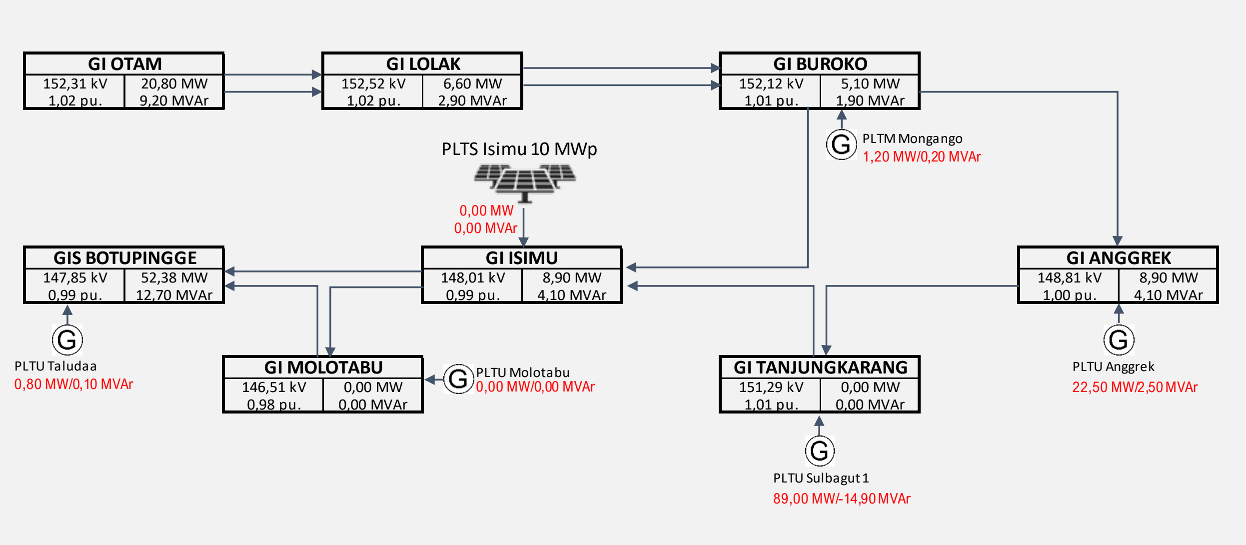


Figure 9. Gorontalo system power before interconnection.

contribution of PLTS Likupang, showing how energy is delivered and the reactive loads present at the various substations and distribution points. This analysis is essential to understand the dynamics of power flow and the critical role that Likupang PV can play in reducing the load on this power system.

Figure 9 shows the Gorontalo system before the PLTS Isimu integration. Similar to Figure 8, the system operates without substantial renewable energy input, with power flowing from conventional sources. The load profile indicates a reliance on fossil-fuel-based generation, highlighting the need for renewable energy diversification. This diagram illustrates the distribution of electrical power through various substations and the impact of the PLTS Isimu on the power flow in the system.

The PLTS Isimu contributes 10 MW of power with a reactive load of 3.30 MVAr to the GI Isimu (148.76 kV). From GI Isimu, a power flow of 8.90 MW with a reactive load of 4.10 MVAr is distributed to GI Anggrek, GI Molotabu, and GIS Botupingge. GI Molotabu did not record any power flow or reactive load GIS. Botupingge received 52.38 MW with a reactive load of 12.70 MVAr, distributed to GI Otam (20.80 MW, 2.90 MVAr) and GI Buroko (5.10 MW, 1.90 MVAr).

GI Otam receives 20.80 MW of power and 2.90 MVAr of reactive load from GI Lolak (6.60 MW, 2.90 MVAr). GI Buroko also receives 1.20 MW of power from PLTM Mongango. GI Anggrek received 8.90 MW of power, 4.10 MVAr of reactive load, and additional power from PLTU Anggrek (22.50 MW, 1.10 MVAr). GI Tanjungkarang did not record any power flow, but PLTU Subagut 1 contributed 89 MW with a reactive load of 17.80 MVAr to the system.

Overall, the diagram in Figure 9 shows how the PLTS Isimu contributes 10 MW to the power system in Gorontalo, helping to meet power demand and demonstrating the importance of renewable energy in maintaining the stability and efficiency of power distribution in the region. The power flow results of the Sulut system in the condition after the interconnection of PLTS Likupang are shown in Figure 10 and Figure 11.

Figure 10 represents the North Sulawesi system after the integration of the PLTS Likupang. This figure illustrates the power flow changes caused by the solar plant's contribution to the grid. While the addition of 15 MW of solar capacity is beneficial, it introduces power fluctuations, especially during periods of inconsistent sunlight. This is where BESS becomes essential. The figure demonstrates how the variability in solar output can cause instability in power distribution if not managed effectively with storage solutions. PLTS Likupang contributes 15 MW of power to GI Likupang (66.00 kV). From GI Likupang, 9.30 MW is distributed to GI MSM. GI MSM distributes 29.30 MW to GI Bitung, which receives 13.10 MW of power from GI Ranomuut.

GI Ranomuut receives 33.30 MW and sends 20.50 MW to GIS Teling (66.20 kV). GIS Teling received 5.40 MW. GI Sawangan received 11.00 MW as well as additional power from PLTA Tanggari. GI Tomohon received 9.70 MW, while GI Tonsealama received 9.00 MW.

Overall, the diagram in Figure 10 shows the critical contribution of PLTS Likupang in distributing power in North Sulawesi, helping to improve the efficiency and stability of the power system.

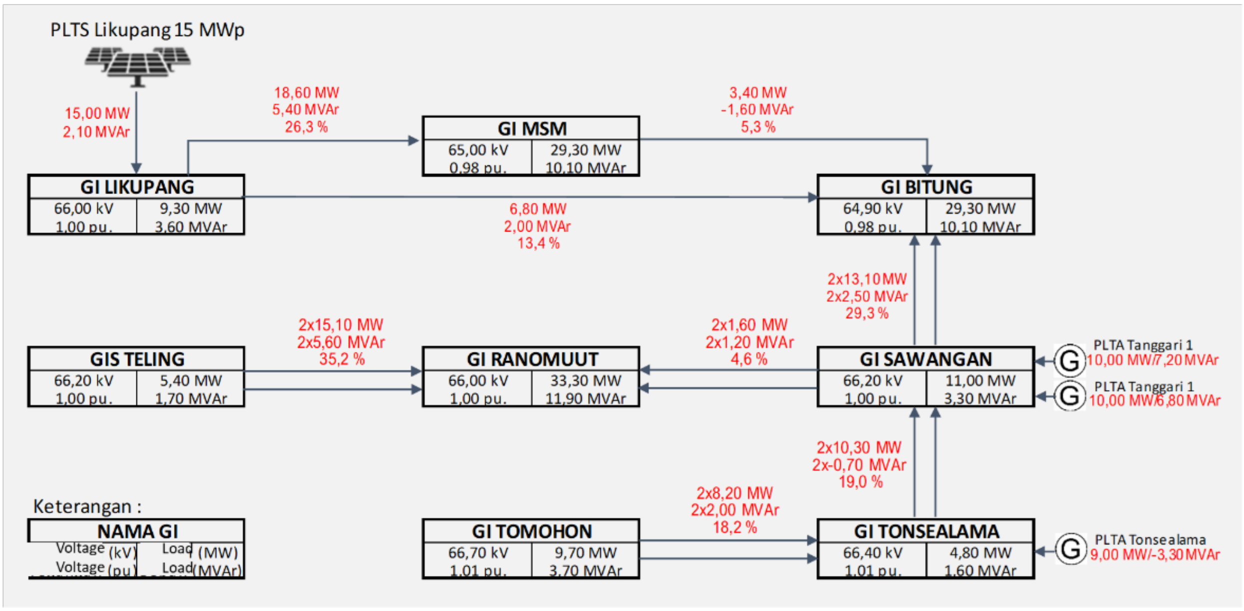


Figure 10. North Sulawesi system power flow after PLTS Likupang interconnection.

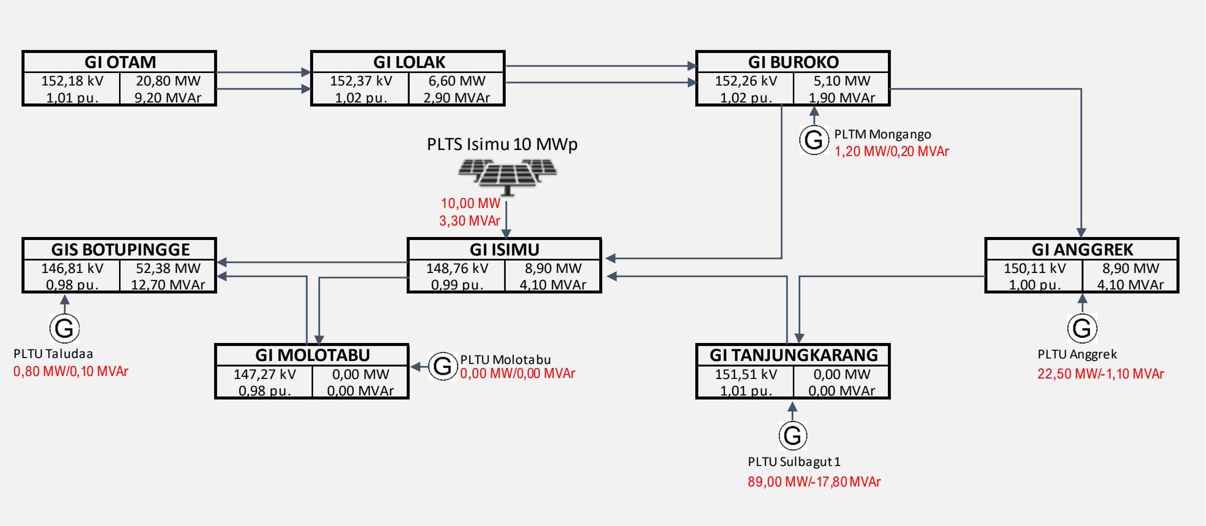


Figure 11. Gorontalo system power flow after interconnection of PLTS Likupang and PLTS Isimu.

Figure 11 shows the Gorontalo system after the interconnection of both PLTS Likupang and PLTS Isimu. The combination of these VRE sources introduces further fluctuations in power flow, which BESS is designed to mitigate. This figure emphasizes the need for energy storage, as the combined variability from the two solar plants can lead to significant instability without proper management. It demonstrates that the BESS helps smooth these fluctuations, ensuring that the grid maintains a stable power flow even during periods of low solar generation. This diagram illustrates how the addition of PLTS Likupang and PLTS Isimu improves the efficiency and stability of the power system in Gorontalo.

The short-circuit current study was conducted to determine the increase in short-circuit current at the substation around the interconnection point due to the operation of PLTS Likupang and PLTS Isimu. Several short-circuit current parameters need to be considered in a short-circuit study.

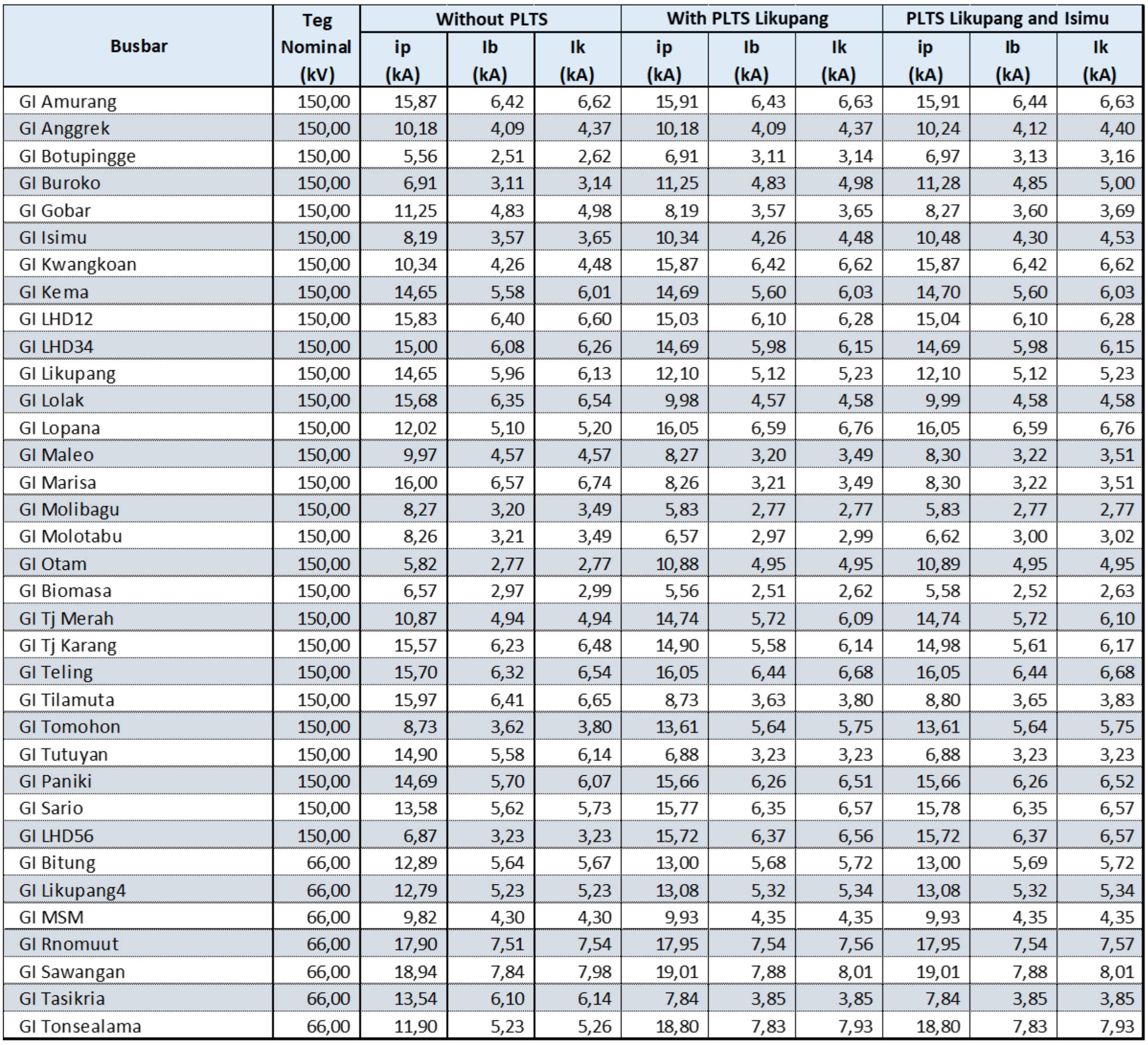
- Initial short-circuit current (Ik") is the value of the RMS AC short-circuit current at the first time a fault occurs (subtransient).
- Making peak short-circuit current (ip) is the highest possible short-circuit current value that can occur.
- Breaking short-circuit current (Ib) is the value of the short-circuit current isolated by the circuit breaker device
- Steady-state short-circuit current (Ik) is the RMS AC short-circuit current value at steady state.

In this study, the given disturbance is a 3-phase to ground fault at the substation around the interconnection point of PLTS Likupang and PLTS Isimu. Short circuit simulations were carried out on scenarios before and after the interconnection of PLTS Likupang and PLTS Isimu.

The power flow profiles in Figure 8 through Figure 10 clearly indicate the challenges posed by integrating intermittent VRE sources into the grid. The figures show that while solar power contributes significantly to the overall energy mix, it introduces variability that can disrupt the grid's stability. The role of BESS, as shown in subsequent analyses, is critical in mitigating these disruptions.

BESS helps to absorb excess energy during peak solar production periods and release energy during times of low production. The presence of BESS minimizes voltage fluctuations and helps maintain grid frequency, ensuring a reliable and stable electricity supply. The integration of a 10 MW/ 5 MWh BESS with PLTS Likupang and PLTS Isimu, as demonstrated in the figures, plays a pivotal role in maintaining power flow consistency, particularly during peak load times and unexpected solar output drops. These figures provide visual evidence of how BESS stabilizes the grid and supports the integration of renewable energy.

Based on Figure 12, it can be seen that the short circuit current increases after the interconnection of PLTS Likupang and after the interconnection of PLTS Likupang and PLTS Isimu. However, although there is an increase in short-circuit current as a consequence of the addition of a new generation in the SulutGo system, the increase in short-circuit current is still below the 150 kV equipment short-circuit current capacity limit, especially the breaking short-circuit current (Ib) is still below the limit value of 40 kA. Thus, based on the short-circuit study aspect, the penetration of PLTS Likupang and PLTS Isimu has no adverse impact on the SulutGo system.



Busbar	Teg Nominal (kV)	Without PLTS			With PLTS Likupang			PLTS Likupang and Isimu		
		ip (kA)	Ib (kA)	Ik (kA)	ip (kA)	Ib (kA)	Ik (kA)	ip (kA)	Ib (kA)	Ik (kA)
GI Amurang	150,00	15,87	6,42	6,62	15,91	6,43	6,63	15,91	6,44	6,63
GI Anggrek	150,00	10,18	4,09	4,37	10,18	4,09	4,37	10,24	4,12	4,40
GI Botupingge	150,00	5,56	2,51	2,62	6,91	3,11	3,14	6,97	3,13	3,16
GI Buroko	150,00	6,91	3,11	3,14	11,25	4,83	4,98	11,28	4,85	5,00
GI Gobar	150,00	11,25	4,83	4,98	8,19	3,57	3,65	8,27	3,60	3,69
GI Isimu	150,00	8,19	3,57	3,65	10,34	4,26	4,48	10,48	4,30	4,53
GI Kwangkoan	150,00	10,34	4,26	4,48	15,87	6,42	6,62	15,87	6,42	6,62
GI Kema	150,00	14,65	5,58	6,01	14,69	5,60	6,03	14,70	5,60	6,03
GI LHD12	150,00	15,83	6,40	6,60	15,03	6,10	6,28	15,04	6,10	6,28
GI LHD34	150,00	15,00	6,08	6,26	14,69	5,98	6,15	14,69	5,98	6,15
GI Likupang	150,00	14,65	5,96	6,13	12,10	5,12	5,23	12,10	5,12	5,23
GI Lolak	150,00	15,68	6,35	6,54	9,98	4,57	4,58	9,99	4,58	4,58
GI Lopana	150,00	12,02	5,10	5,20	16,05	6,59	6,76	16,05	6,59	6,76
GI Maleo	150,00	9,97	4,57	4,57	8,27	3,20	3,49	8,30	3,22	3,51
GI Marisa	150,00	16,00	6,57	6,74	8,26	3,21	3,49	8,30	3,22	3,51
GI Molibagu	150,00	8,27	3,20	3,49	5,83	2,77	2,77	5,83	2,77	2,77
GI Molotabu	150,00	8,26	3,21	3,49	6,57	2,97	2,99	6,62	3,00	3,02
GI Otam	150,00	5,82	2,77	2,77	10,88	4,95	4,95	10,89	4,95	4,95
GI Biomasa	150,00	6,57	2,97	2,99	5,56	2,51	2,62	5,58	2,52	2,63
GI Tj Merah	150,00	10,87	4,94	4,94	14,74	5,72	6,09	14,74	5,72	6,10
GI Tj Karang	150,00	15,57	6,23	6,48	14,90	5,58	6,14	14,98	5,61	6,17
GI Teling	150,00	15,70	6,32	6,54	16,05	6,44	6,68	16,05	6,44	6,68
GI Tilamuta	150,00	15,97	6,41	6,65	8,73	3,63	3,80	8,80	3,65	3,83
GI Tomohon	150,00	8,73	3,62	3,80	13,61	5,64	5,75	13,61	5,64	5,75
GI Tutuyan	150,00	14,90	5,58	6,14	6,88	3,23	3,23	6,88	3,23	3,23
GI Paniki	150,00	14,69	5,70	6,07	15,66	6,26	6,51	15,66	6,26	6,52
GI Sario	150,00	13,58	5,62	5,73	15,77	6,35	6,57	15,78	6,35	6,57
GI LHD56	150,00	6,87	3,23	3,23	15,72	6,37	6,56	15,72	6,37	6,57
GI Bitung	66,00	12,89	5,64	5,67	13,00	5,68	5,72	13,00	5,69	5,72
GI Likupang4	66,00	12,79	5,23	5,23	13,08	5,32	5,34	13,08	5,32	5,34
GI MSM	66,00	9,82	4,30	4,30	9,93	4,35	4,35	9,93	4,35	4,35
GI Rnomuut	66,00	17,90	7,51	7,54	17,95	7,54	7,56	17,95	7,54	7,57
GI Sawangan	66,00	18,94	7,84	7,98	19,01	7,88	8,01	19,01	7,88	8,01
GI Tasikria	66,00	13,54	6,10	6,14	7,84	3,85	3,85	7,84	3,85	3,85
GI Tonsealama	66,00	11,90	5,23	5,26	18,80	7,83	7,93	18,80	7,83	7,93

Figure 12. 3 Phase short circuit current to SulutGo system ground.

Figure 12 shows the results of the short circuit analysis for various substations in the North Sulawesi electricity system under three conditions: without PLTS, with PLTS Likupang, and with PLTS Likupang and PLTS Isimu. In the condition without PLTS, the short circuit current at various substations varies; for example, at GI Anggrek, the peak current (ip) is 10.18 kA, the base current (Ib) is 4.09 kA, and the short circuit current (Ik) is 4.37 kA. With the addition of PLTS Likupang, short circuit currents are decreased in several substations, such as in GI Likupang ip, which decreased from 14.65 kA to 12.10 kA and Ik from 6.13 kA to 5.23 kA. Adding PLTS Isimu alongside PLTS Likupang increased the short circuit current. For example, GI Anggrek ip increased to 10.24 kA and Ik to 4.40 kA. Overall, this table shows that the addition of PLTS Likupang and PLTS Isimu solar farms significantly increases the short-circuit currents at various substations, indicating the need for system adjustments to handle such increased currents to maintain the power grid's stability and safety.

C. Analysis of the impact of BESS on the electricity system

1) Power fluctuations and BESS impact on frequency stability

Operation testing of the 15 MW PLTS Likupang solar power plant was conducted on February 18 - 20, 2019. The test results are used to calculate the battery capacity needed in the SulutGo system with the primary function of frequency regulation. In testing the simulation model, an instantaneous decrease in the output power of PLTS Likupang was carried out by the nominal power of the plant to determine the system response to the most extreme load changes at PLTS Likupang. This simulation is also carried out to validate the model used so that simulation results are obtained close to actual conditions. The simulation results when there is a load decrease of 15.0 MW at PLTS Likupang can be seen in Figure 13.

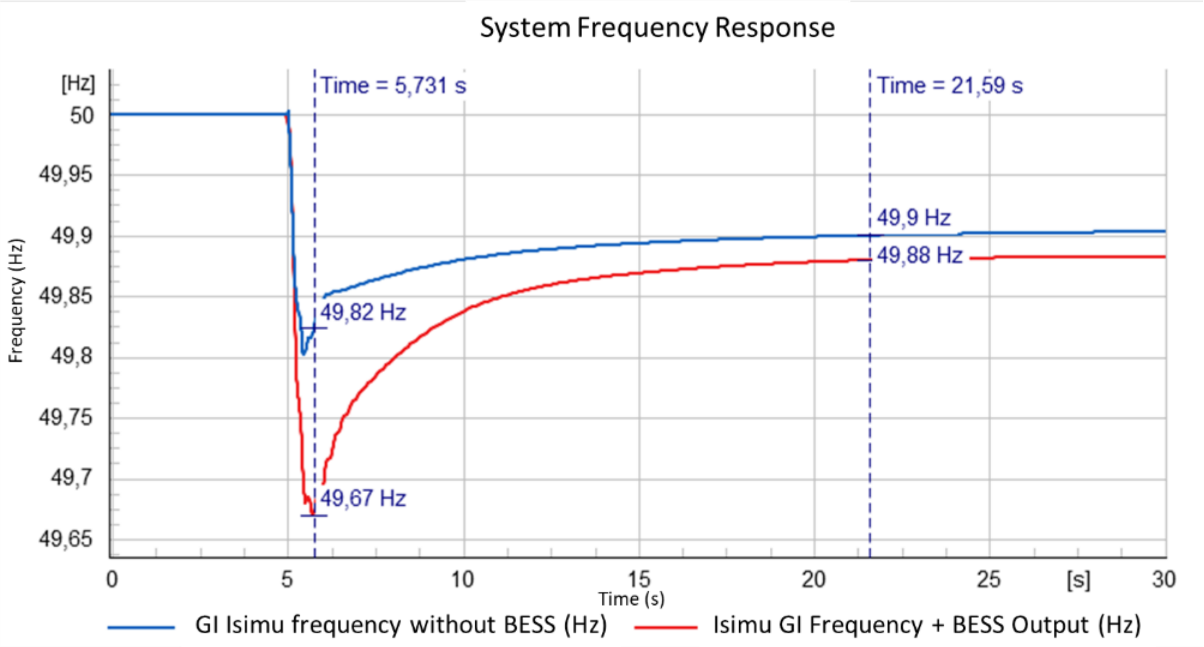


Figure 13. The frequency response curve of the system under transient testing.

Figure 13 shows a graph of the frequency response of the electrical system at GI Isimu to transient disturbances, both with and without BESS. The vertical axis shows the frequency in Hertz (Hz), while the horizontal axis shows the time in seconds (s). Initially, the system frequency is around 50 Hz. When the fault occurred at 5.731 s, the frequency drops dramatically. Without BESS (red line), the frequency drops to 49.67 Hz before starting to rise again. With the BESS (blue line), the frequency only drops to 49.82 Hz, showing less impact from the disturbance. After the disturbance, both systems start to recover the frequency. The system without BESS takes longer to reach stability, with a frequency of around 49.88 Hz at 21.59 seconds.

In contrast, the system with BESS recovers faster and reached stability at 49.9 Hz within the same time. Overall, these graphs show that using BESS helps reducing the impact of transient disturbances on system frequency, speed up recovery, and improve frequency stability. Integrating BESS in the power grid can increase the system's resilience to frequency fluctuations due to sudden disturbances.

2) Output power and BESS response during transient disturbances

Additional tests measured the output power of the Likupang solar plant and BESS during transient testing. Figure 14 shows that the BESS mitigates sharp drops in output power and maintains stability even after disturbances, with output stabilizing at around 6 MW compared to the uncontrolled fluctuation seen without BESS.

The graph in Figure 14 shows the output power of PLTS Likupang coupled with BESS during transient testing. The vertical axis shows the power in megawatts (MW), while the horizontal axis shows the time in seconds (s). Initially, the output power of the Likupang solar power plant is around 15 MW. At the time of 5.61 seconds, a disturbance causes a sudden drop in power. The red line that remains flat shows the constant load of PLTS Likupang. However, the blue line shows PLTS Likupang load, and the BESS output shows the response to the disturbance. When the fault occurs, the output power drops to 7.846 MW. After that, the power decreases gradually until it stabilizes at around 6 MW. The BESS helps cushion the sharp power drop and keep the power output stable after the disturbance. This graph shows that integrating the BESS with the PLTS Likupang helps reducing the impact of transient disturbances on output power. Although the output power drops sharply at the beginning of the disturbance, the BESS helps stabilizing and maintaining the output power at a more stable level. Integrating the BESS is critical to improving the resilience and stability of solar power systems against sudden power fluctuations.

3) BESS power supply and frequency regulation

The impact of a 10 MW/ 5 MWh BESS on frequency regulation was also tested over longer durations, and the results are shown in Figure 15 and Figure 16. With BESS, the system's frequency fluctuates within a smaller range, dropping to only 49.82 Hz, while BESS supplies an additional 7.8 MW to compensate for the loss of solar generation.

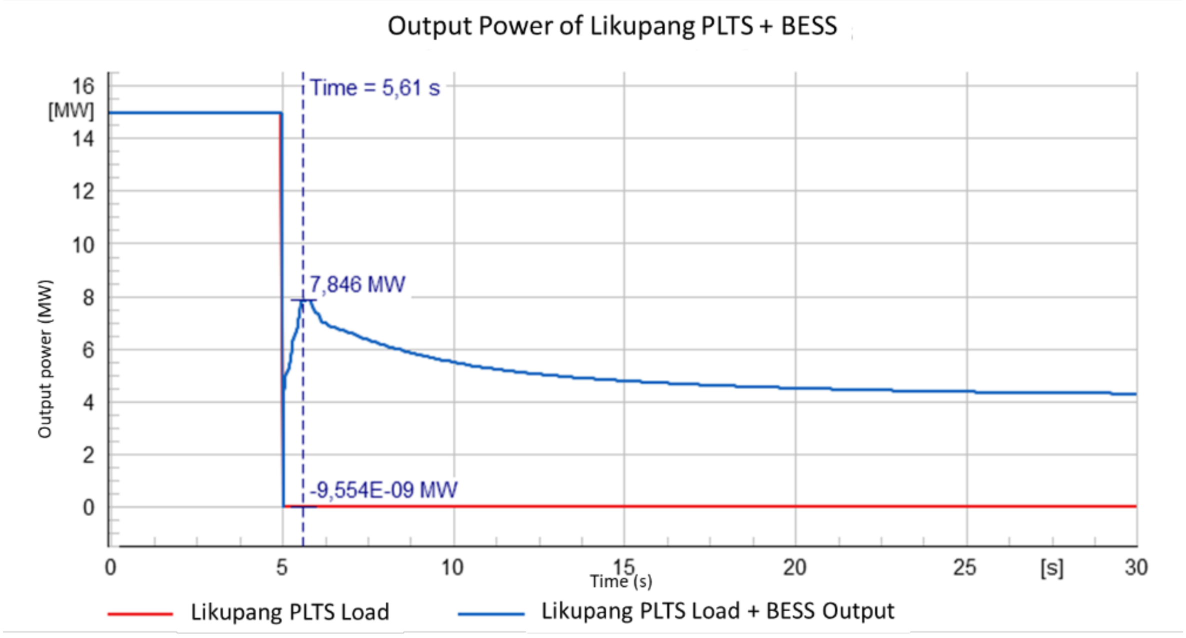


Figure 14. Total output power curves of PLTS Likupang and BESS under transient testing.

Figure 15 shows the output power of BESS during the transient test. The vertical axis shows the power in megawatts (MW), while the horizontal axis shows the time in seconds (s). With the addition of a 10 MW/5 MWh BESS, the frequency drop only reaches 49.82 Hz (a decrease of 0.18 Hz). This happens because the BESS, which functions as frequency regulation, increases the power supply to the system and compensates for the reduction of PLTS power reasonably quickly. In this condition, BESS's power supply increases to about 7.8 MW in 0.82 seconds. In a longer simulation duration, adding 10 MW/5 MWh BESS only causes a decrease in frequency to 49.82 Hz (a reduction of 0.18 Hz). This shows that the BESS can provide additional power supply to the system when the solar power output decreases and absorbs power from the system when there is an increase in the solar power output.

Furthermore, a continuous transient simulation for 5 minutes (300 seconds) was conducted to observe the fluctuations in the output power of the solar power plant and BESS. These results can be seen in Figure 16. Figure 16 shows the system's frequency response at GI Likupang to changes in the output power of PLTS

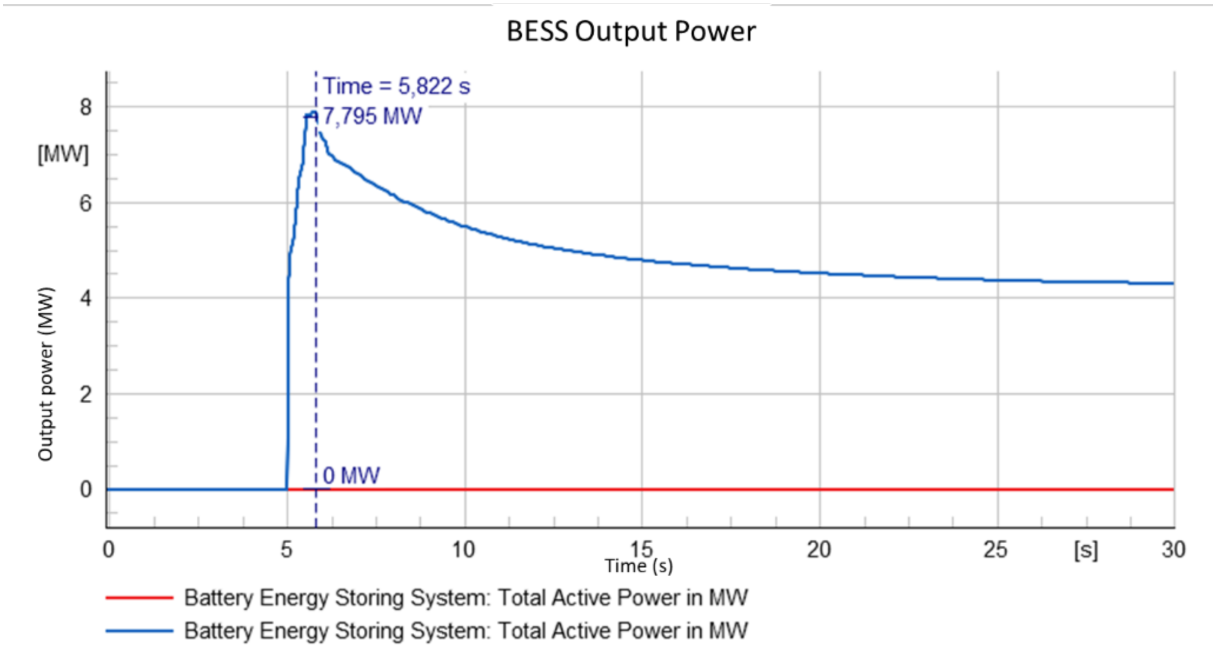


Figure 15. BESS output power curve in transient testing.

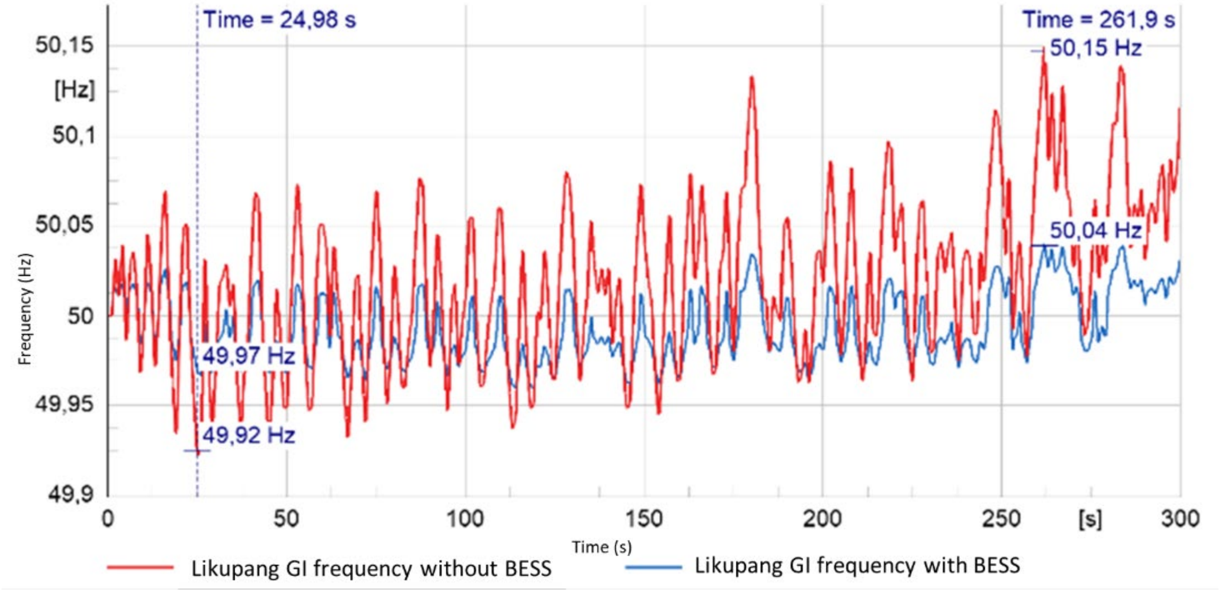


Figure 16. Frequency response of the system without and with BESS.

Likupang, both without BESS (red line) and with BESS (blue line). The vertical axis shows the frequency in Hertz (Hz), while the horizontal axis shows the time in seconds (s). Initially, the system frequency hovers around 50 Hz. When the disturbance occurres at time 24.98 s, the frequency begins to fluctuate. Without the BESS, the frequency dropps to 49.92 Hz and fluctuates sharply with greater amplitude. The peak frequency reaches 50.15 Hz at the time of 261.9 seconds. With BESS, the frequency dropps less, to 49.97 Hz, and fluctuates with a smaller amplitude than without BESS. The frequency peak with BESS reaches 50.04 Hz simultaneously, indicating more damped and stable fluctuations.

Overall, these graphs show that using BESS helps dampening frequency fluctuations due to disturbances, keeping the system frequency stable. Integrating BESS into the power grid can improve the system's resilience and stability against frequency disturbances, reduce the risk of blackouts, and ensure a more reliable electricity supply. These results highlight the crucial role of BESS in ensuring stable system frequency and preventing large deviations during power imbalances caused by solar variability.

4) BESS performance in smoothing output power and voltage stability

BESS also helps stabilizing voltage fluctuations at the Likupang Substation. Figure 17 shows that, without BESS, the substation's voltage fluctuates between 4 and 14 kV. However, with BESS, these fluctuations are significantly reduced, stabilizing between 6 and 8 kV.

The graph in Figure 17 shows the output power of BESS over 300 seconds. The vertical axis shows the power in megawatts (MW), while the horizontal axis shows the time in seconds (s). The horizontal red line at 0 MW shows the condition without the BESS, while the fluctuating blue line shows the output power of the BESS during that period. Initially, the BESS output power shows small fluctuations of around 0 MW. Over time, the power fluctuations become more significant, with the peak value reaching around 6 MW and the lowest value around -6 MW. These fluctuations reflect the BESS's response in balancing the system's power to maintain frequency stability. Overall, this graph shows that BESS is active in responding to load changes and disturbances in the system. With significant power fluctuations, BESS stabilizes the electricity system by storing power when in excess and releasing it when in shortage. This strengthens the system's resilience to disturbances and ensures a more stable and reliable electricity supply.

Finally, an analysis of the total output power of PLTS Likupang and BESS is shown in Figure 18. The graph in Figure 18 shows the total output power of the PLTS Likupang with and without BESS for 300 seconds. The vertical axis shows the power in megawatts (MW), while the horizontal axis shows the time in seconds (s). The red line shows the output power of PLTS Likupang without BESS, while the blue line shows the output power with BESS. Initially, the output power of PLTS Likupang without BESS shows significant fluctuations, with peaks reaching around 14 MW and decreasing to around 4 MW. Without BESS, these power fluctuations are more critical and more frequent, reflecting the instability in the power supply. With the BESS, the power fluctuations are more controllable. The output power still fluctuates, but with a smaller amplitude, and

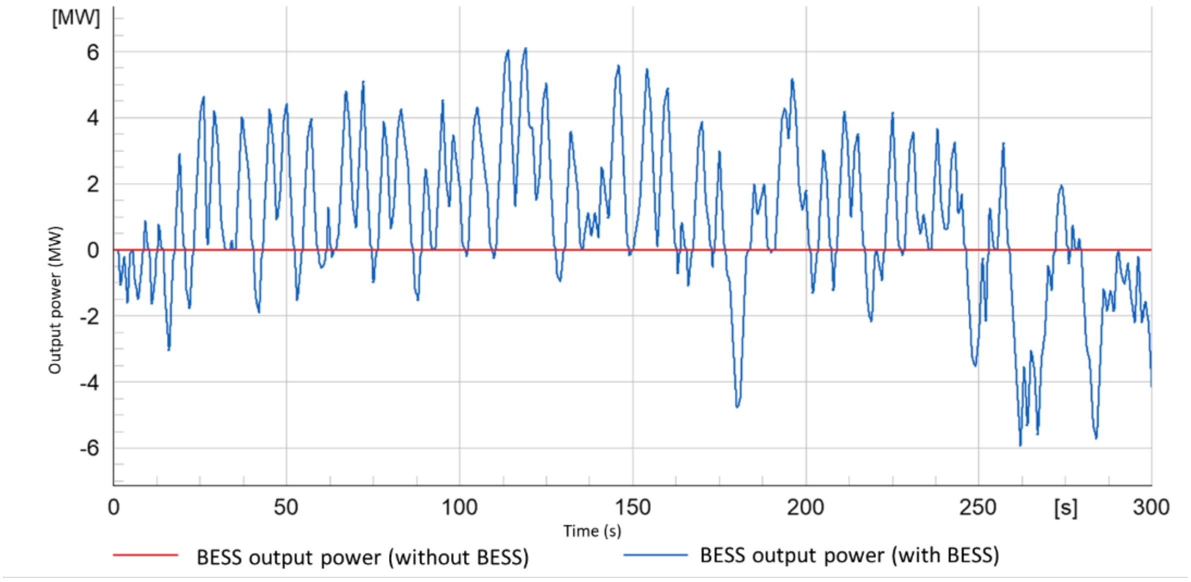


Figure 17. BESS output power.

is more stable than without BESS. The blue line shows that the output power is more consistent at around 6-8 MW, although some peaks and dips still exist. Overall, this graph shows that integrating the BESS helps stabilizing the output power of PLTS Likupang.

BESS plays a role in dampening power fluctuations, ensuring a more stable and reliable electricity supply. This is important to maintain the stability of the electricity system and reduce the risk of disruption due to sudden changes in power. Indirectly, the addition of BESS also improve of voltage quality at the substation closest to the PLTS interconnection point in the system. This happens because adding BESS can reduce fluctuations in the PLTS power supply to the system, which reduces fluctuations in power transfer on several transmission lines at several substations around the PLTS. The impact of adding BESS on the GI Likupang voltage as the closest GI to PLTS Likupang can be seen in Figure 19.

Figure 19 shows the GI Likupang voltage with and without BESS for 300 seconds. The vertical axis shows the voltage in kilovolts (kV), while the horizontal axis shows the time in seconds (s). The red line shows the voltage without BESS, while the blue line shows the voltage with BESS. Initially, the GI Likupang voltage without BESS shows significant fluctuations, with peaks

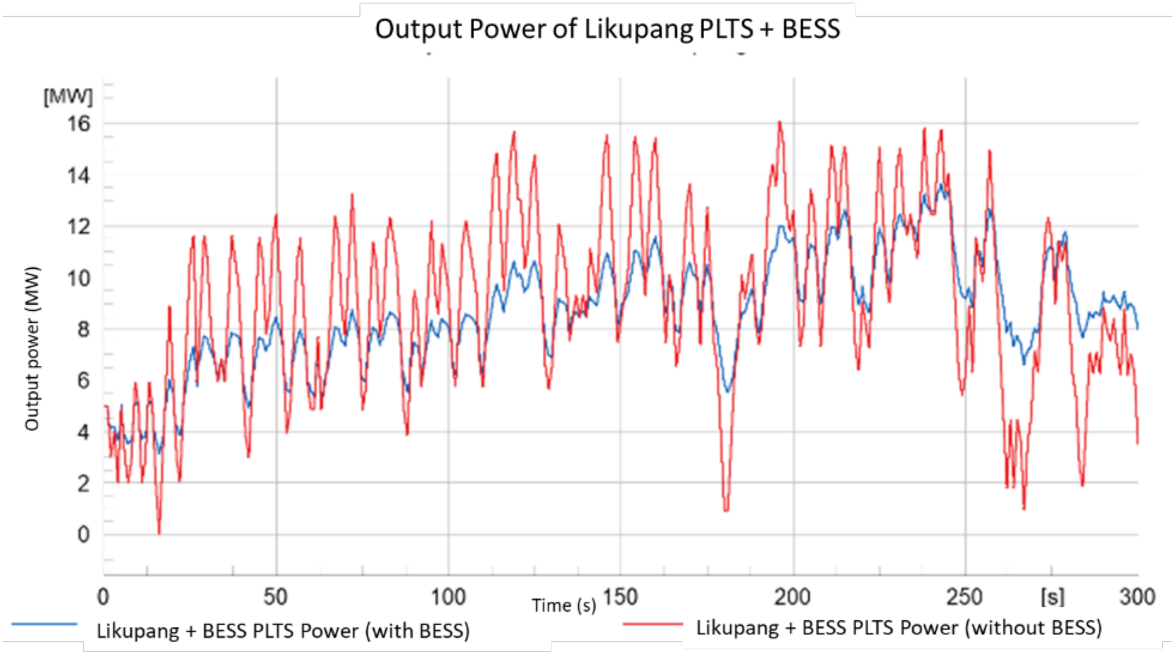


Figure 18. Total output power of PLTS Likupang and BESS.

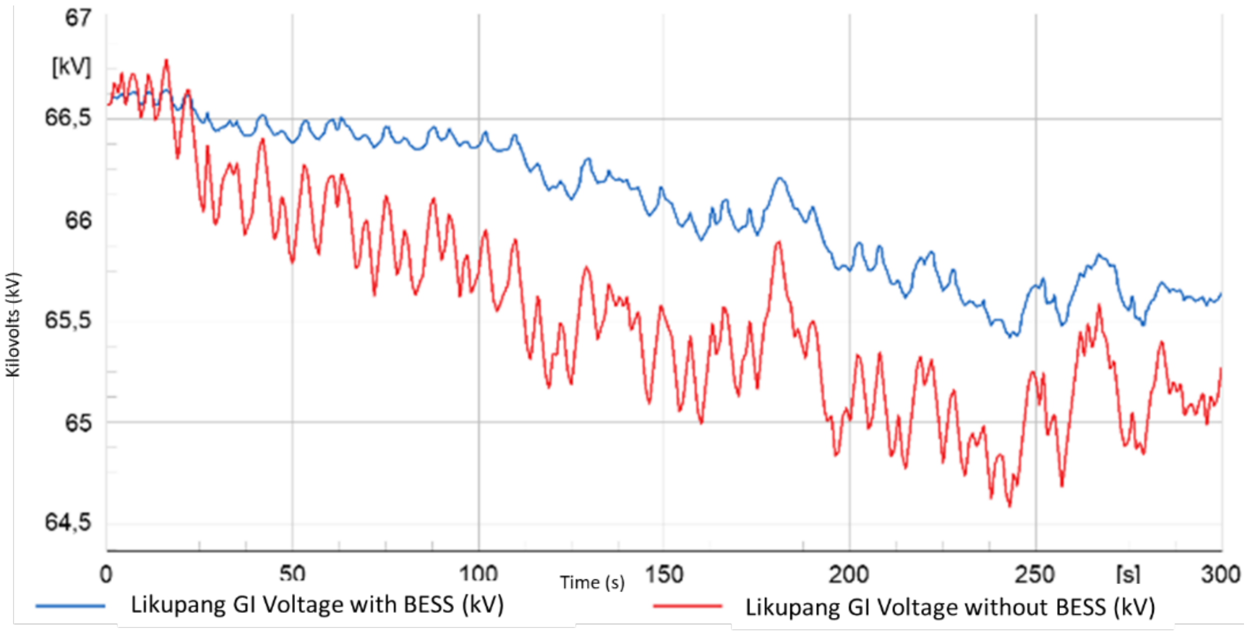


Figure 19. GI Likupang voltage curve.

reaching around 14 kV and decreasing to around 4 kV. Without BESS, these voltage fluctuations are more critical and frequent, reflecting the instability in the power supply. With the BESS, voltage fluctuations are more controllable. The voltage still fluctuates, but with a smaller amplitude, and is more stable than without the BESS. The blue line shows that the voltage is more consistent around 6-8 kV, although some peaks and dips still exist. This graph shows that integrating BESS helps stabilizing the voltage at the GI Likupang. BESS plays a role in dampening voltage fluctuations, ensuring a more stable and reliable electricity supply. This is important for maintaining the stability of the electricity system and reducing the risk of disruptions due to sudden changes in voltage.

In this study, the frequency response curves are presented for PLTS Isimu, while the output power curves are shown for the Likupang solar power plant. This differentiation in the presentation of results is primarily due to the specific operational characteristics and data availability at each plant, as well as the distinct focus of the analysis for each site.

The Isimu plant was selected for the frequency response analysis because of its direct impact on grid frequency stability, particularly due to its geographic location and its integration into a section of the grid where frequency fluctuations are more pronounced. Given its proximity to critical transmission lines, Isimu's role in managing frequency deviations is significant for the stability of the entire system. Thus, the frequency response analysis was prioritized at this site to evaluate how BESS could mitigate such fluctuations in this specific context.

On the other hand, the Likupang plant was chosen for the output power analysis due to its larger capacity (15 MW) and the more detailed monitoring of power fluctuations. The higher installed capacity at Likupang provides a more substantial dataset for analyzing the effectiveness of BESS in smoothing out power output variations. Since Likupang experiences more notable fluctuations due to its larger scale, the focus on output power helps to illustrate the critical role of BESS in stabilizing energy supply from larger VRE sources.

While it would have been ideal to conduct both types of tests at both plants, logistical constraints such as the availability of real-time operational data, the capacity of each plant, and the specific challenges each site presents led to the decision to focus the analyses differently for each location. This approach helps to captures the most relevant aspects of grid stability at both sites, allowing for a comprehensive understanding of how BESS can address site-specific issues.

The implications of the results of analyzing the performance of the BESS on solar power plants for global and national electricity systems are very significant. Globally, using BESS to address intermittency in VRE generation, such as solar PV, can improve grid reliability and stability [28][29]. The use of BESS enables the storage of surplus energy when energy production exceeds consumption and provides power when production is reduced, thereby reducing the risk of power supply disruptions caused by weather fluctuations. This supports the global transition towards more excellent renewable energy sources, reduces dependence on fossil fuels, and contributes to reducing carbon emissions.

5) Comparative analysis with previous studies

The findings of this study are consistent with global research on the benefits of BESS for stabilizing renewable energy sources. For instance, Mallapragada *et al.* (2020) demonstrated the long-term value of BESS in balancing grid frequency under conditions of high solar and wind generation [6]. Similarly, Zhao *et al.* (2023) highlighted BESS's role in improving grid stability during transient events, noting that BESS systems mitigate the risks of blackouts and improve recovery time after disturbances [12].

While previous studies have often focused on larger-scale renewable energy systems, this research specifically addresses the challenges faced in Indonesia's decentralized grid. The results are particularly significant for regions like North Sulawesi and Gorontalo, where weather fluctuations are common. BESS integration in such regions helps achieve national renewable energy targets by ensuring stable and reliable electricity transmission, as demonstrated by this study.

Nationally, especially in Indonesia, integrating BESS with solar power plants can help achieving the renewable energy mix target of 23 % by 2025 [30][31]. Given the country's vast geography and high variations in sunlight intensity, using BESS can ensure that electricity generated by solar farms can be stably transmitted to the grid, even in areas with high weather fluctuations, such as North Sulawesi and Gorontalo. This will improve the reliability of the power system and reduce the potential for disruptions, thereby supporting local economic development and increasing sustainable access to electricity for the community.

IV. Conclusion

The findings of this study demonstrate that integrating BESS with solar power plants in North Sulawesi and Gorontalo effectively reduces the effects of intermittency from VRE sources. This integration improves grid stability by minimizing frequency and voltage fluctuations, which are crucial for ensuring a reliable and stable electricity supply. The analysis shows that BESS helps mitigating the impact of sudden power drops from solar PV output, especially during transient disturbances, thus reducing the risk of blackouts and supply interruptions. These results provide essential insights for grid operators and policymakers on the practical applications of BESS in stabilizing renewable energy systems. The impact of this research extends beyond technical improvements to Indonesia's broader energy transition goals. By showcasing the potential of BESS to support renewable energy integration this study contributes to the country's efforts to achieve its 23 % renewable energy target by 2025. Moreover, the findings emphasize the global importance of BESS in accommodating a higher share of renewable energy, reducing reliance on fossil fuels, and enhancing energy security. Future research should explore different BESS technologies and assess their long-term economic and environmental implications, while broader geographical studies could provide a deeper understanding of BESS scalability in diverse energy systems.

Declarations

Author contribution

Mudakir: Writing - Original Draft, Writing - Review & Editing, Conceptualization, Formal analysis, Investigation, Visualization, Supervision. **Aripriharta**: Writing - Original Draft, Writing - Review & Editing, Conceptualization, Investigation, Validation, Data Curation. **Aji Prasetya Wibawa**: Formal analysis, Resources, Software, Visualization, Funding acquisition

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The use of AI or AI-assisted technologies

During the preparation of this work the authors used **DigSilent PowerFactory 2022** in order to compile the analysis. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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References

[1] R. R. Hernandez, S. M. Jordaan, B. Kaldunski, and N. Kumar, "Aligning climate change and sustainable

development goals with an innovation systems roadmap for renewable power," *Front. Sustain.*, vol. 1, Dec. 2020.

[2] Osman *et al.*, "Cost, environmental impact, and resilience of renewable energy under a changing climate: a review," *Environ. Chem. Lett.*, vol. 21, no. 2, pp. 741–764, Apr. 2023.

[3] K. Abbass, M. Z. Qasim, H. Song, M. Murshed, H. Mahmood, and I. Younis, "A review of the global climate change impacts, adaptation, and sustainable mitigation measures," *Environ. Sci. Pollut. Res.*, vol. 29, no. 28, pp. 42539–42559, Jun. 2022.

[4] H. Ajibade, C. O. Ujah, K. C. Nnakwo, and D. V. V. Kallon, "Improvement in battery technologies as panacea for renewable energy crisis," *Discov. Appl. Sci.*, vol. 6, no. 7, p. 374, Jul. 2024.

[5] P. Pathak, R. R Srivastava, "Renewable energy as a sustainable alternative: A way forward," in *Alternative Energy Resources*, ed., vol. 99, The Handbook of Environmental Chemistry, vol. 99, Springer Cham., 2020, pp. 317–321.

[6] D. S. Mallapragada, N. A. Sepulveda, and J. D. Jenkins, "Long-run system value of battery energy storage in future grids with increasing wind and solar generation," *Appl. Energy*, vol. 275, p. 115390, Oct. 2020.

[7] X. Chen and W. Cao, *Advancements in Energy Storage Technologies*. In *Tech*, May 2, 2018.

[8] M. Jafari, M. Korpås, and A. Botterud, "Power system decarbonization: Impacts of energy storage duration and interannual renewables variability," *Renew. Energy*, vol. 156, pp. 1171–1185, Aug. 2020.

[9] Z. Rostamnezhad, N. Mary, L.-A. Dessaint, and D. Monfet, "Electricity Consumption Optimization Using Thermal and Battery Energy Storage Systems in Buildings," *IEEE Trans. Smart Grid*, vol. 14, no. 1, pp. 251–265, Jan. 2023.

[10] X. Chen, Y. Chen, Z. Lin, X. Mao, J. Chen, and Z. Zhang, "Design of High-Power Energy Storage Bidirectional Power Conversion System," in *2020 24th International Conference Electronics*, Jun. 2020, pp. 1–6.

[11] Parthasarathy, H. Hafezi, and H. Laaksonen, "Integration and control of lithium-ion BESSs for active network management in smart grids: Sundom smart grid backup feeding case," *Electr. Eng.*, vol. 104, no. 2, pp. 539–553, Apr. 2022.

[12] Zhao, P. B. Andersen, C. Træholt, and S. Hashemi, "Grid-connected battery energy storage system: a review on application and integration," *Renew. Sustain. Energy Rev.*, vol. 182, p. 113400, Aug. 2023.

[13] Kebede *et al.*, "Techno-economic analysis of lithium-ion and lead-acid batteries in stationary energy storage application," *J. Energy Storage*, vol. 40, p. 102748, Aug. 2021.

[14] J. M. Bhatt, P. V. Ramana, and J. R. Mehta, "Performance assessment of valve regulated lead acid battery for E-bike in field test," *Mater. Today Proc.*, vol. 49, 2022, pp. 2058–2065.

[15] K. Santos-Pereira, J. D. F. Pereira, L. S. Veras, D. L. S. Cosme, D. Q. Oliveira, and O. R. Saavedra, "The requirements and constraints of storage technology in isolated microgrids: a comparative analysis of lithium-ion vs. lead-acid batteries," *Energy Syst.*, May 2021.

[16] N. Collath, B. Tepe, S. Englberger, A. Jossen, and H. Hesse, "Aging aware operation of lithium-ion battery energy storage systems: A review," *J. Energy Storage*, vol. 55, p. 105634, Nov. 2022.

[17] M. Gutsch and J. Leker, "Global warming potential of lithium-ion battery energy storage systems: A review," *J. Energy Storage*, vol. 52, p. 105030, Aug. 2022.

[18] K. Sharma *et al.*, "Imperative Role of Photovoltaic and Concentrating Solar Power Technologies towards Renewable Energy Generation," *Int. J. Photoenergy*, vol. 2022, pp. 1–13, Jan. 2022.

[19] M. Soomar, A. Hakeem, M. Messaoudi, P. Musznicki, A. Iqbal, and S. Czapp, "Solar Photovoltaic Energy Optimization and Challenges," *Front. Energy Res.*, vol. 10, May 2022.

[20] Ramos, M. Tuovinen, and M. Ala-Juusela, "Battery Energy Storage System (BESS) as a service in Finland: Business model and regulatory challenges," *J. Energy Storage*, vol. 40, p. 102720, Aug. 2021.

[21] M. N. Pratama, M. I. Hashfi, R. O. G. Munthe, K. M. Banjar-Nahor, and N. Hariyanto, "Operational Road Map in North Sulawesi and Gorontalo Power Grid Considering the Intermittent Photovoltaic Penetration," in *2022 5th International Conference on Power Engineering and Renewable Energy (ICPERE)*, Nov. 2022, pp. 1–6.

[22] M. N. Pratama, M. I. Hashfi, I. F. Dermawan, K. M. Banjar-Nahor, and N. Hariyanto, "Method To Improve The Accuracy Of PV Curtailment To Maintain The System Stability in North Sulawesi and Gorontalo Power Grid," in *2023 4th International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, Aug. 2023, pp. 243–247.

[23] El Kharbachi, O. Zavorotynska, M. Latroche, F. Cuevas, V. Yartys, and M. Fichtner, "Exploits, advances and challenges benefiting beyond Li-ion battery technologies," *J. Alloys Compd.*, vol. 817, p. 153261, Mar. 2020.

[24] M. Armand *et al.*, "Lithium-ion batteries – Current state of the art and anticipated developments," *J. Power Sources*, vol. 479, p. 228708, Dec. 2020.

[25] F. Díaz-González *et al.*, "A hybrid energy storage solution based on supercapacitors and batteries for the grid integration of utility scale photovoltaic plants," *J. Energy Storage*, vol. 51, p. 104446, Jul. 2022.

[26] R. D. Trevizan, J. Obert, V. De Angelis, T. A. Nguyen, V. S. Rao, and B. R. Chalamala, "Cyberphysical Security of Grid Battery Energy Storage Systems," *IEEE Access*, vol. 10, pp. 59675–59722, 2022.

[27] K. T., C. R. S., J. D. N. J., and C. K., "Design of IoT based smart compact energy meter for monitoring and controlling the usage of energy and power quality issues with demand side management for a commercial building," *Sustain. Energy, Grids Networks*, vol. 26, p. 100454, Jun. 2021.

[28] L. Deguenon, D. Yamegueu, S. Moussa kadri, and A. Gomna, "Overcoming the challenges of integrating

variable renewable energy to the grid: A comprehensive review of electrochemical battery storage systems," *J. Power Sources*, vol. 580, p. 233343, Oct. 2023.

[29] S. R. Sinsel, R. L. Riemke, and V. H. Hoffmann, "Challenges and solution technologies for the integration of variable renewable energy sources—a review," *Renew. Energy*, vol. 145, pp. 2271–2285, Jan. 2020.

[30] H. B. Apribowo, Sarjiya, S. P. Hadi, and F. D. Wijaya, "Integration of Battery Energy Storage System to Increase Flexibility and Penetration Renewable Energy in Indonesia: A Brief Review," in *2022 5th International Conference on Power Engineering and Renewable Energy (ICPERE)*, Nov. 2022, pp. 1–6.

[31] N. Reyseliani and W. W. Purwanto, "Pathway towards 100% renewable energy in Indonesia power system by 2050," *Renew. Energy*, vol. 176, pp. 305–321, Oct. 2021.