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Optimizing Capacity of a Hybrid Diesel-Solar PV-BESS on Nusa Penida Island Using a Load Following Approach

[1]Oktavianus Enggar Bowo Suasono, [2*]Faiz Husnayain
[1,2]*Departement of Electrical Engineering, Faculty of Engineering*
[1,2] *University of Indonesia*
Depok, Indonesia
Email : [1]oktavianus.enggar@ui.ac.id, [2*]faiz.h@ui.ac.id

Abstract - *Indonesia, as the world's largest archipelagic country, faces substantial challenges in achieving equitable energy access, particularly in remote regions. These areas are predominantly reliant on Diesel Power Plants (PLTD), which result in high operational costs, logistical complexities in fuel supply, and considerable carbon emissions. Despite these limitations, remote regions possess abundant renewable energy resources, particularly solar energy. However, the intermittency of solar generation due to weather fluctuations hampers its reliability as a primary energy source. To address these challenges, this study proposes the implementation of a hybrid energy system integrating Solar Photovoltaic (PV) systems and Battery Energy Storage Systems (BESS), supported by a load-following dispatch strategy and optimal capacity planning. The objective is to improve both the reliability and efficiency of the local power system. The study was conducted on Nusa Penida Island, specifically at the 20 kV Kutampi Substation, which is interconnected with the existing diesel power infrastructure. The methodology encompasses a comprehensive literature review, secondary data acquisition, manual system sizing, and simulation-based analysis. PV capacity potential was assessed using PVSyst software, while power flow and voltage simulations were performed for three operational scenarios: (i) existing diesel-only configuration (baseline), (ii) hybrid Diesel-PV-BESS configuration, and (iii) PV-BESS configuration without diesel generators. Power system simulations were carried out using a computer-based electrical analysis platform to evaluate the technical impact of integrating renewable energy into the local grid. Simulation results demonstrate that the integration of PV and BESS enhances voltage stability and ensures a more reliable energy supply. Furthermore, techno-economic analysis reveals that the hybrid Diesel-PV-BESS configuration yields the most favourable outcome, achieving a Levelized Cost of Energy (LCOE) of IDR 3,088 per kWh. These findings underscore the potential of hybrid renewable energy systems as a viable solution for sustainable energy development in remote island regions.*

Keywords: *Nusa Penida Island, Load Flow, Load Following, Hybrid Power Plant, LCOE*

I. INTRODUCTION

Indonesia continues to face significant challenges in achieving equitable energy distribution, particularly in remoteregions, which are generally not connected to the national grid and remain heavily reliant on diesel power plants characterized by high operational costs and substantial carbon emissions. In contrast, these regions possess abundant renewable energy resources, particularly solar energy [1].

The integration of Renewable Energy Sources (RES) with Battery Energy Storage Systems (BESS) in a hybrid configuration presents a strategic solution to reduce dependency on fossil fuels, enhance power system reliability, and support national initiatives such as the diesel phase-out program and the broader energy transition agenda [2].

However, suboptimal operation and maintenance of solar PV systems have resulted in low performance ratios and poor economic returns. Nusa Penida, the selected case study area, exhibits high solar irradiance potential but remains predominantly powered by diesel power plant. Therefore, this research is essential to design and optimize a hybrid PV-BESS system as a sustainable, reliable, and clean energy solution for electricity provision in remote regions [3].

II. RESEARCH METHODS

2.1 Dispatch Strategy

A dispatch strategy refers to the operational approach used to manage and coordinate the output of various power generation sources within an energy system to meet the electricity demand in real time. In the context of a hybrid power system (such as Diesel–PV–BESS), it involves determining when and how much each component—diesel generators, photovoltaic (PV) units, and battery energy storage systems (BESS)—should generate or supply energy.

There are several types of dispatch strategies, including load following, cycle charging, peak shaving, and renewable priority dispatch, each optimized for different objectives like fuel efficiency, cost minimization, or maximizing renewable energy use.

2.1.1 Cycle Charging (CC)

Cycle Charging is an operational strategy designed to maximize generator efficiency by allowing the generator to simultaneously serve the load and charge the batteries. Excess generator capacity is utilized to replenish battery storage, reducing the frequency of generator start-stop cycles and thus extending generator lifespan. This strategy ensures that batteries remain at a high state of charge (SOC), minimizing deep discharge cycles. However, fuel consumption under cycle charging is typically higher than in the load-following strategies, as the generator operates continuously regardless of load level.

2.1.2 Load Following (LF)

Load Following is an operational strategy where the generator is activated solely to meet the instantaneous load demand, without charging the batteries. When the renewable generation (e.g., from PV) is insufficient, the generator provides only the required load power. Surplus energy is not directed toward battery charging unless explicitly programmed. This strategy minimizes fuel consumption—an important consideration in remote areas where fuel transport costs are high—and maximizes the use of renewable resources. When renewable generation exceeds the load, excess energy is used to charge the batteries. Economically, Load Following offers lower operational costs, though battery replacement costs may be higher due to more frequent deep cycling. This strategy is particularly suitable for regions with high and stable solar irradiation throughout the year.

2.1.2 Leve Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) is a standardized economic metric used to evaluate the average cost per kilowatt-hour (kWh) of electricity generated by a power generation system over its entire operational lifespan. It incorporates capital expenditures, operation and maintenance costs, fuel expenses (if applicable), and system lifetime, thereby providing a comprehensive basis for comparing the cost-effectiveness of different energy technologies. The Levelized Cost of Energy (LCOE) is a standardized economic metric widely used in techno-economic evaluations to determine the average cost of electricity generation per kilowatt-hour (kWh) over the entire lifecycle of a power generation system. It integrates all relevant cost components, including initial capital investment, operation and maintenance (O&M) expenses, fuel costs (if applicable), and replacement costs, discounted over the system's expected operational period. LCOE provides a consistent framework for comparing the cost-effectiveness of various generation technologies—both conventional and renewable—on a per-unit energy basis, making it a critical tool for energy planning, investment decision-making, and policy analysis.

$$\text{LCOE} = \sum_{n=1}^{N} \left(\frac{\frac{In + Mn + Fn}{(1+d)^n}}{\frac{En}{(1+d)^n}} \right) \tag{1}$$

2.2 Research Methods

This research employs a structured nine-stage methodology to evaluate the technical and economic feasibility of integrating a hybrid Photovoltaic–Battery Energy Storage System (PV-BESS) into the isolated power grid of Nusa Penida, Indonesia. The process begins with problem formulation, objective setting, and framework development. Data were sourced from PLN ULP Bali Timur and PLN Indonesia Power Services, along with supporting information from solar and geospatial databases. Load and capacity analysis determined the energy demand and appropriate sizing of PV modules and battery storage. PV system design was conducted using PVSyst software, incorporating local irradiance data to simulate performance. The system was then modeled using power system analysis software to assess technical viability across three scenarios: diesel-only, hybrid diesel-PV-BESS, and hybrid PV-BESS. Technical feasibility was evaluated based on voltage regulation and load coverage criteria. Subsequently, a techno-economic analysis was conducted to compute the Levelized Cost of Energy (LCOE) for hybrid configurations. Cost-benefit comparisons were used to ensure the PV-BESS or Diesel-PV-BESS systems achieved economic viability. The final stage integrated technical and financial findings to validate the proposed hybrid system as a reliable and cost-effective solution for enhancing energy access in Nusa Penida.

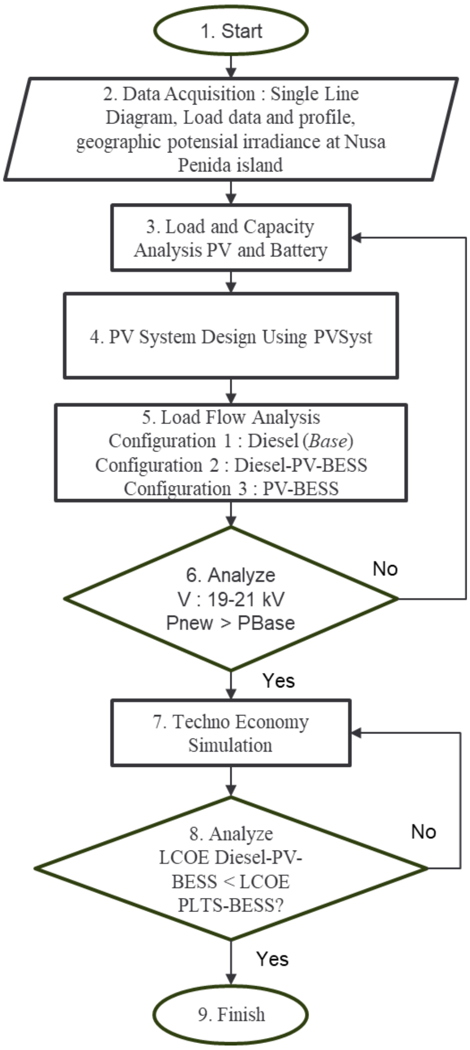

Figure 1. A methodological approach to the study of Optimizing Capacity of a Hybrid Diesel-Solar PV-Battery Energy Storage System on Nusa Penida Island Using a Load Following Approach

2.3 Research Site Data

The following data were collected and utilized as inputs for software-based modeling and simulation in this study:

2.3.1 Research Location

The selected study location is the Indonesia Power Service diesel power plant (PLTD) situated on Nusa Penida Island, part of Klungkung Regency in the Province of Bali. This location was chosen due to its isolated electrical network, making it ideal for a hybrid renewable energy integration study. Nusa Penida is located at coordinates Latitude -08.7346°, Longitude 115.5378°. The deployment of renewable energy, particularly solar photovoltaic (PV) systems, is a promising solution in this region, given its high Global Horizontal Irradiance (GHI), averaging 5.197 kWh/m²/day. The installation of PV systems is complemented by battery storage to ensure energy availability. By integrating the existing diesel power plant with renewable generation and energy storage, it is expected to achieve an optimal hybrid power configuration in terms of both cost efficiency and operational reliability [4].

2.3.2 Load Profile

The load profile of the PLTD operated by Indonesia Power Services on Nusa Penida Island was compiled over a 24-hour period (00:00 to 23:00 WITA), with the peak demand reaching 4,898.47 kW, as illustrated in Figure 2 below.

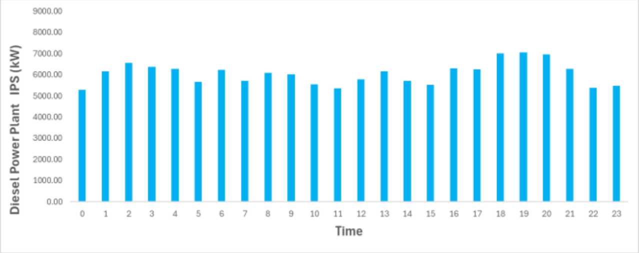

Figure 2. Load Profile Indonesia Power Services Diesel Power Plant

2.3.3 Solar Irradiation and Temperature Data

Solar irradiation and ambient temperature are critical factors for PV system deployment, as they directly affect the potential energy output. Based on data from NASA's Prediction of Worldwide Energy Resource (POWER) database, the specific irradiation levels for the study area are summarized in Table 1.

Table 1. Irradiation data from NASA [5]

Month	Clearness Index	Daily Radiation (kWh/m^2/day)
January	0.453	4.930
February	0.464	5.040
March	0.518	5.430
April	0.556	5.390
May	0.591	5.190
June	0.585	4.840
July	0.565	4.790
August	0.576	5.330
September	0.588	5.950
October	0.580	6.190
November	0.524	5.670
December	0.488	5.280
Annual Avg	0.540	5.340

The annual average daily solar radiation is approximately 5.34 kWh/m²/day, with the highest value occurring in October (6.190 kWh/m²/day) and the lowest in July (4.790 kWh/m²/day).

2.3.4 Computer-Based Techno-Economic Modeling Method

The modeling methodology applied in this study utilizes a computer-based techno-economic simulation tool to evaluate and optimize the performance of a hybrid power system integrated with diesel power plant on Nusa Penida. This software enables comprehensive technical and economic analysis for multi-source energy systems including PV, Diesel, and Battery Energy Storage Systems (BESS).

2.3.4.1 Parameters for Techno-Economic Simulation

Two primary categories of input parameters are required: technical specifications and economic data of system components. Economic parameters include component costs, operational and maintenance (O&M) costs, and component lifespans, which are critical in determining the system's lifecycle cost. Table 2 outlines the major components and associated costs used in the simulation.

Table 2. Input Parameters for Techno-Economic Simulation

Item	Price	Volume	Source
PV Module JKM385M-72-V (Jinko Solar)	IDR 360,289,147,000.00	240.353 pcs	A1SOLARSTONE
Inverter SUN2000-175KTL-H0 (Huawei)	IDR 7,828,285,119.00	519 pcs	Alibaba
Solar PV Cable (DC Cable)	IDR 1,550,000.00	1000 meters	Tokopedia
AC Cable	IDR 2,450,000,000.00	1000 meters	Tokopedia
Battery CATL O852280-P Lithium Iron Phosphate	IDR 843,292,000,000.00	843.292 pcs	Alibaba
Inverter ABB PS1000 690Vac/3L.2	IDR 61,440,000,000.00	480 pcs	Alibaba
Transformer	IDR 250,000,000,000.00	2 pcs	Alibaba
PV Shipping Import Cost from China to Indonesia	IDR 81,065,058,075.00		
Inverter Shipping Import Cost from China to Indonesia	IDR 1,761,364,151.78		
Consultant cost (Engineering, FS, Installation)	IDR 6,550,000,000.00		
Others (Mounting, accessories, etc)	IDR 16,150,000,000.00		
Total Investment	**IDR 1,630,827,404,345.77**		
Operational Cost	IDR 4,892,482,213,04	IDR/*year*	
Maintenance Cost	IDR 11,415,791,830.42	IDR/*year*	

III. RESULT AND ANALYSIS

3.1 System Design

3.1.1 Installed PV System Capacity Calculation

To determine the installed capacity of the photovoltaic (PV) system and the required number of solar panels, it is necessary to first specify the type of solar modules and inverters to be used. In this study, JA Solar panels with a nominal capacity of 550 Wp and ABB inverters were initially considered.

Prior to conducting the calculations for installed capacity and the number of PV modules to be deployed, the specific type and rating of the solar panels and inverters must be defined. For the final configuration, Jinko Solar PV modules rated at 385 Wp and Huawei inverters rated at 200 kW were selected. Table 3 presents the technical specifications of the selected PV module, while Table 4 provides the inverter specifications used in this study.

Table 3. PV Solar Panel Specification

Item	Unit
Manufacture	JA Solar
Model	JAM72S30 525-550/MR
Technology	Si-mono
Number of Cell in Series	144
Number of Cell in parallel	1
Max. Power (Pmax)	550 Wp
Voltage Maximum (Vmp)	4196 V
Current Maximum (Imp)	13.11 A
Open Circuit Voltage (Voc)	49.90 V
Short Circuit Current (Isc)	14.00 A
Modul eff STC	21.3 %
Dimension	2279 x 1134 x 34 mm

The graph presented in Figure 3 illustrates the relationship between output voltage (V) and output power (P) of a solar panel. The black curve represents the performance under Standard Test Conditions (STC). The peak of the curve indicates the Maximum Power Point (MPP), which signifies the optimal operating point where the panel produces the highest possible power output. As solar irradiance increases, the power output also increases, following a rise in voltage up to its maximum point. This characteristic curve highlights the critical importance of operating the photovoltaic panel at its Maximum Power Point to ensure optimal efficiency of the PV system.

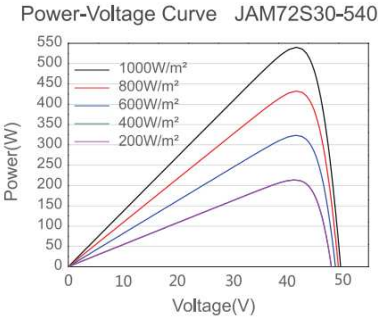

Figure 3. Power-Voltage Characteristic [6]

Figure 4 illustrates the current-voltage (I–V) characteristic curve of a solar panel. As the level of solar irradiance increases, the resulting current output increases proportionally. The curve demonstrates that the output current of the solar panel remains relatively constant as the voltage increases, up to the maximum power point voltage (*Vmp*). Beyond this point, the current drops sharply to nearly zero as it approaches the open-circuit voltage (V_{oc}). This curve reflects the response behaviour of the solar panel under varying irradiance conditions.

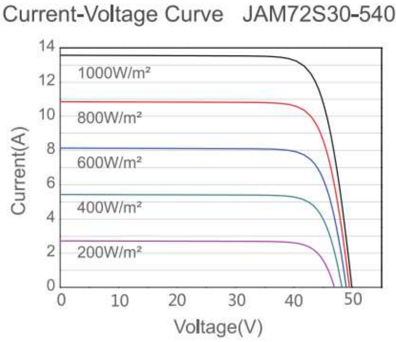

Figure 4. Current-Voltage Characteristic [6]

Table 4. PV Inverter Specification [7]

Type	**Unit**
Manufacture	Huawei
Model	SUN2000-215KTL-H0
Input	
Max. Input Voltage	1500 V
Max Current MPPT	30 A
Max Shor Circuit Current per MPPT	50 A
Nominal Voltage	550 V
MPPT Operating Voltage Range	500-1500 V
Nominal Input Voltage	1080 V
Number of Input	18
Number of MPP Tracker	9
Output	
Nominal AC Active Power	200 kW
Max. AC Apparent Power	215 kVA
Nominal Output Voltage	800 V (3W+PE)
Frequency	50 Hz
Nominal Output Current	144.4 A
Max. Output Current	155.2 A

Table 5. Battery Specification for BESS [8]

Type	**Unit**
Manufacture	CATL
Type	O852280-P Lithium Iron Phosphate
Voltage per Cell	1331.2 Vdc
Capacity	372.7 kW

Table 6. BESS Inverter Specification [9]

Type	**Unit**
Manufacture	ABB Inverter
Type	PS1000 690Vac/3L.2
Nominal Power	1500 kVA
Capacity	372.7 kW

The next step involves calculating the required installed capacity of the PV system by determining the daily energy demand currently supplied by the existing diesel power plant and the average solar irradiance intensity. As shown in Table 7, the total exported energy from the diesel power plant existing in 2024 amounted to 39,188,387 kWh.

Table 7 Actual Exported Energy of the IPS Diesel Power Plant in 2024

Month	Energy
January	4,138,799
February	3,896,594
March	4,067,201
April	4,317,680
May	3,173,081
June	2,815,440
July	2,842,752
August	2,782,832
September	2,646,547
October	2,941,899
November	2,777,762
December	2,787,800
Energy Total	**39,188,387**

For the research data, the highest monthly exported energy value was recorded in April, amounting to 4,317,680 kWh. This corresponds to an average daily energy export of 143,922 kWh. This value is used as the basis for calculating the required capacity of the PV-BESS system.

Battery Calculation

$$BESS\ Capacity = \frac{DEC\ [Wh]-(ADL[W]\ x\ 4\ h)}{\eta batt\ x\ DODmax(\%)} \tag{2}$$

Where :
DEC (Daily Energy Consumption) : 201,491 kWh
ADL (Average Daily Limitation) : 8,395 kW
$\eta batt$ (Baterai Efficiency) : 90%
DoD_{max} (Deep of Discharge) : 80%
BESS Capacity = 154,850 kWh

$$Battery\ Capacity = \frac{Total\ Daily\ Load\ (Wh)x\ DOA}{Voltage\ System\ (V)x\ DOD} \tag{3}$$

Where :
Total Daily Load : 201,491 kWh
DOA (Day of Autonomy) : 3 days
Voltage system : 1331.2 Vdc
DoD (Deep of Discharge) : 80%
Battery Capacity = 568,000 Ah

PV Inverter Calculation

$$PV\ Capacity\ Inverter\ = \frac{DEC\ [Wh]/PV\ Ratio}{PSH\ [jam]x\ PSHcorrection} \tag{4}$$

Where :
DEC Total (Daily Energy Consumption) : BESS capacity (kWh) + DEC = 356,340 kWh
PV Ratio : 0.85
PSH (Peak Sun Hour): 4.74 h
PSH Correction: 0.85
PV Capacity Inverter = 103,833 kW

- PV Total Capacity

$$PV\ Total\ Capacity\ (kWp) = PV\ Inverter\ Cap\ [W]x\ \frac{AC}{DC}\ Ratio \tag{5}$$

Where:
PV Inverter Capacity: 201,491 kWh
AC/DC Ratio: 1.25
PV Total Capacity = 129,791 kWp
Mount of PV Panel:

$$N_{PV} = \frac{PV_{CAP}(kWp)}{P_O\ (Wp)} \tag{6}$$

= 235,983 PV Panel

- BESS Inverter Capacity

$$BESS\ Inverter\ Capacity = \ PV\ Inverter\ Capacity\ [W] - ADL \tag{7}$$

= 95,437 kW

3.1.2 PVSyst Simulation

After determining the installed PV system capacity, the next step involves inputting the collected data into the PVSyst software for simulation and analysis. These inputs include site-specific data such as area size, geographical coordinates (latitude and longitude), tilt angle, and azimuth angle obtained from the Global Solar Atlas website, as well as the technical specifications of the selected PV modules and inverters. The proposed location for the installation of the hybrid PV system with BESS is at the Kutampi Substation, situated at coordinates Latitude -08.7346°, Longitude 115.5378°.

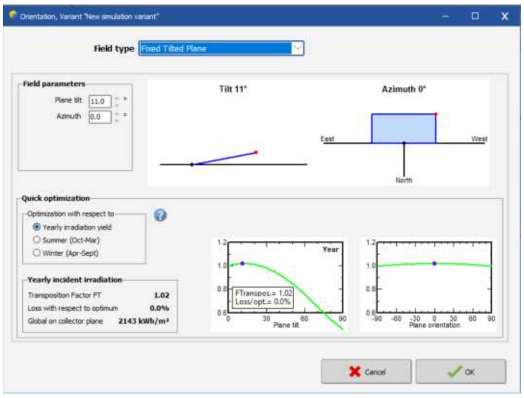
Orientation, Variant "New simulation variant"
Field type: Fixed Tilted Plane
Field parameters
Plane tilt: 11.0 °
Azimuth: 0.0 °
Quick optimization
Optimization with respect to
● Yearly irradiation yield
○ Summer (Oct-Mar)
○ Winter (Apr-Sept)
Yearly incident irradiation
Transposition Factor FT: 1.02
Loss with respect to optimum: 0.0%
Global on collector plane: 2143 kWh/m²
FTranspos.= 1.02
Loss/opt.= 0.0%

Figure. 5 Optimal Tilt Angle and Azimuth Orientation

Figure 5 illustrates the orientation of a solar panel in terms of tilt and azimuth angles. The tilt angle of 11° represents the inclination relative to the horizontal plane, indicating that the panel is angled towards the sun to optimize solar energy capture. The image on the right depicts the panel's azimuth orientation, where an azimuth angle of 0° corresponds to a north-facing direction.

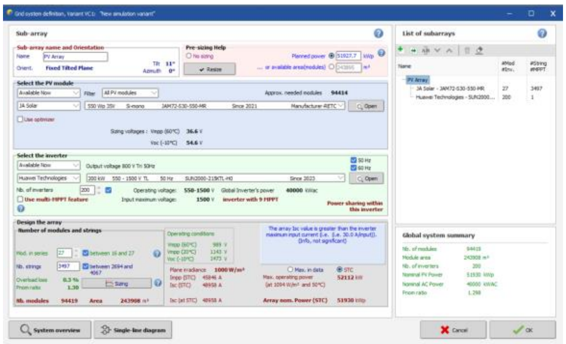
Grid system definition, Variant VC1: "New simulation variant"
Sub-array
Sub-array name and Orientation
Name: PV Array
Orient.: Fixed Tilted Plane
Tilt: 11°
Azimuth: 0°
Pre-sizing Help
○ No sizing
Planned power ● 51927.7 kWp
... or available area(modules) ○ 243895 m²
Select the PV module
Available Now
Filter: All PV modules
Approx. needed modules: 94414
JA Solar
550 Wp 35V Si-mono JAM72-S30-550-MR Since 2021 Manufacturer-RETC
☐ Use optimizer
Sizing voltages : Vmpp (60°C) 36.6 V
Voc (-10°C) 54.6 V
Select the inverter
Available Now
Output voltage 800 V Tri 50Hz
☑ 50 Hz
☑ 60 Hz
Huawei Technologies
200 kW 550 - 1500 V TL 50 Hz SUN2000-215KTL-H0 Since 2023
Nb. of inverters: 200 ☑
Operating voltage: 550-1500 V
Global Inverter's power: 40000 kWac
☐ Use multi-MPPT feature
Input maximum voltage: 1500 V
inverter with 9 MPPT
Power sharing within this inverter
Design the array
Number of modules and strings
Mod. in series: 27 ☑ between 16 and 27
Nb. strings: 3497 ☑ between 2694 and 4067
Overload loss: 0.3 %
Pnom ratio: 1.30
Nb. modules: 94419
Area: 243908 m²
Operating conditions
Vmpp (60°C) 989 V
Vmpp (20°C) 1143 V
Voc (-10°C) 1473 V
Plane irradiance: 1000 W/m²
Impp (STC) 45846 A
Isc (STC) 48958 A
Isc (at STC) 48958 A
The array Isc value is greater than the inverter maximum input current (i.e. (i.e. 30.0 A/input)). (Info, not significant)
○ Max. in data ● STC
Max. operating power (at 1094 W/m² and 50°C): 52112 kW
Array nom. Power (STC): 51930 kWp
List of subarrays
Name | #Mod #Inv. | #String #MPPT
PV Array
JA Solar - JAM72-S30-550-MR | 27 | 3497
Huawei Technologies - SUN2000... | 200 | 1
Global system summary
Nb. of modules: 94419
Module area: 243908 m²
Nb. of inverters: 200
Nominal PV Power: 51930 kWp
Nominal AC Power: 40000 kWAC
Pnom ratio: 1.298

Figure 6. PV and Inverter Entry Data in PVSyst

After entering all the parameter data into the respective input menus, the simulation generates output data including predicted energy production, active power output, and the sun path diagram over the course of a year. The simulation also provides an estimate of the land area required for the PV system installation. Subsequently, on-site area measurements were conducted based on the output data from PVSyst, as illustrated in Figure 7.

Figure 7. Available Area in Nusa Penida

Figure 8 below presents the PV system layout generated in PVSyst, consisting of 35 strings with 27 modules in series. The system includes a total of 200 inverters, each rated at 20 kW, which are planned to be implemented at the diesel power plant site in Nusa Penida.

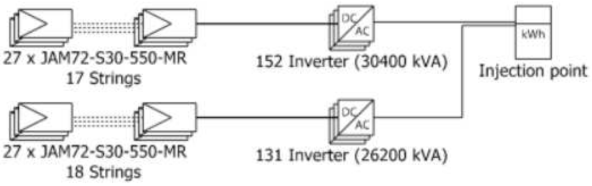

Figure 8. Single Line Diagram PV and Inverter

3.1.3 Computer-Based Power System Software Simulation

Further analysis regarding system optimization and reliability is carried out through simulations using a computer-based power system software platform. This simulation process is conducted in three configuration stages:

1. Operation of the existing diesel power plant – *Base Case*
2. Hybrid operation of Diesel and PV-BESS
3. Hybrid operation of PV-BESS only

Table 8. Actual Load in Nusa Penida

Outgoing Bus	Actual Load (MW)
Lembongan	3.4
Ceningan	4.75
Bunga Mekar	1.02
Ped	2.45
Tanglad	0.54
Karang Sari	1.05
Suana	0.81
Total Load	**14.02**

The initial step involves constructing a Single Line Diagram (SLD) of the existing operational configuration within the simulation software. The SLD presented in Figure 9 illustrates that the primary power source originates from the Kutampi Substation, which interconnects with three diesel power systems—Indonesia Power Service diesel, diesel power plant Genindo, and diesel power plant Panca—as well as an existing Solar Hybrid Power Plant (PLHS).

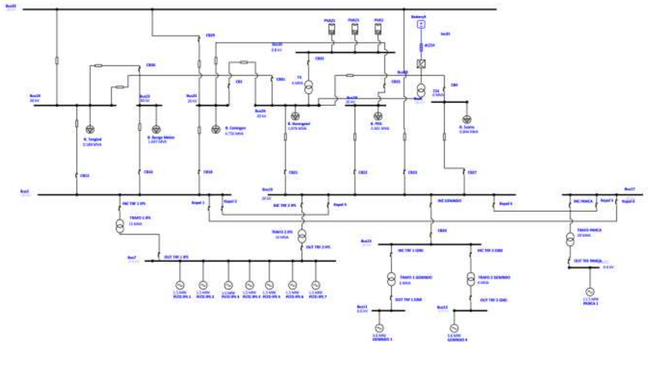

Figure 9. Single Line Diagram Existing Diesel Operation (Base Condition)

After constructing the Single Line Diagram (SLD), the next step involves performing a load flow simulation for the existing operational configuration. Based on the simulation results, voltage and load readings were recorded and presented in Table 9. and Table 10.

Table 9. Load Result at Diesel Power Plant Configuration (Base Case)

Power Plant	Load Result (MW)
Diesel IPS	4.46
Diesel Genindo	2.50
Diesel Panca	2.97
PV-BESS Eksisting	4.02
Total Beban	**13.95**

Table 10. Voltage Result at Outgoing Bus

Bus Outgoing	Voltage (kV)
Bus 2 (P. Tanglad)	18.12
Bus 23 (P. Bunga Mekar)	18.14
Bus 24 (P. Ceningan)	17.94
Bus 26 (P. Karang Sari)	18.68
Bus 28 (P. Ped)	17.92
Bus 5 (P. Suana)	18.67
Bus 33 (P. Lembongan)	18.08

Subsequently, a simulation was conducted for the hybrid operational configuration involving three diesel generators integrated with the PV-BESS system, based on the Single Line Diagram (SLD) shown in Figure 3.8 Out of the seven existing diesel units installed, four units were intentionally shut down to observe the load distribution shift to the designed PV-BESS system.

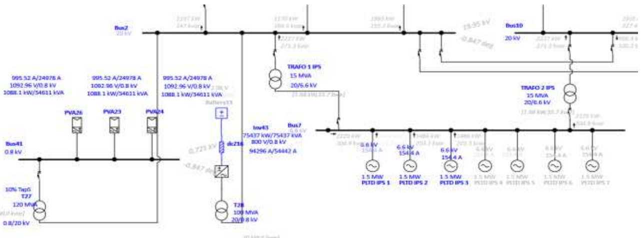

Figure 10. Single Line Diagram Diesel-PV-BESS Configuration

After completing the Single Line Diagram (SLD), the process continued with a load flow simulation of the existing operational configuration. The simulation results were then used to record voltage and load measurements, which are presented in Table 11 and Table 12.

Table 11. Load Result at Diesel-PV-BESS Configuration

Power Plant	Load (MW)
Diesel IPS	0.88
Diesel Genindo	0.09
Diesel Panca	0.59
PV-BESS Eksisting	4.14
PV-BESS New	8.38
Total Beban	**14.08**

Tabel 12. Voltage Result at Outgoing Bus

Bus Outgoing	Voltage (kV)
Bus 2 (P. Tanglad)	18.92
Bus 23 (P. Bunga Mekar)	18.94
Bus 24 (P. Ceningan)	18.75
Bus 26 (P. Karang Sari)	19.49
Bus 28 (P. Ped)	18.73
Bus 5 (P. Suana)	19.47
Bus 33 (P. Lembongan)	18.80

From the simulation results of the Diesel–PV–BESS configuration, as shown in the table, it can be observed that the load distribution among the existing generators and the hybrid PV-BESS system is well-balanced. Additionally, the voltage profile on the feeder side shows significant improvement. The following table presents a comparison of the voltage improvements:

Table 13. Comparation of Voltage Result at Diesel-PV-BESS Configuration

Bus	Voltage (kV) Before	Voltage(kV) After	% Voltage Increase
Bus 2 (P. Tanglad)	18.12	18.92	4%
Bus 23 (P. Bunga Mekar)	18.14	18.94	4%
Bus 24 (P. Ceningan)	17.94	18.75	4%
Bus 26 (P. Karang Sari)	18.68	19.49	4%
Bus 28 (P. Ped)	17.92	18.73	4%
Bus 5 (P. Suana)	18.67	19.47	4%
Bus 33 (P. Lembongan)	18.08	18.80	4%

A system design was then carried out for the hybrid PV–BESS operational configuration by shutting down all seven IPS diesel generator units, as illustrated in Figure 11.

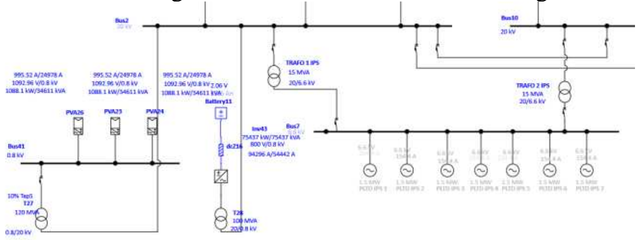

Figure 11. Single Line Diagram PV-BESS Configuration

The load flow simulation results indicate noticeable improvements, with the load on the PV–BESS system being normally distributed as shown in the table 14. Additionally, voltage levels across each feeder have improved, as presented in table 15.

Table 14. Load Result at PV-BESS Configuration

Power Plant	Load (MW)
Diesel IPS	0.88
Diesel Genindo	0.09
Diesel Panca	0.59
PV-BESS Eksisting	4.14
PV-BESS New	8.38
Total Beban	**14.08**

Tabel 15. Voltage Result at Outgoing Bus

Bus Outgoing	Voltage (kV)
Bus 2 (P. Tanglad)	19.03
Bus 23 (P. Bunga Mekar)	19.05
Bus 24 (P. Ceningan)	18.87
Bus 26 (P. Karang Sari)	19.6
Bus 28 (P. Ped)	18.84
Bus 5 (P. Suana)	19.58
Bus 33 (P. Lembongan)	19.0

As shown in Table 14, the load readings under the newly configured PV–BESS system indicate a well-balanced distribution across the existing generators and the hybrid PV–BESS unit. Moreover, the voltage profile along the feeder lines has improved significantly, as detailed in table 15. A comparative summary of the voltage improvement is presented in the following table:

Table 16. Comparation of Voltage Result at PV-BESS Configuration

Bus	Voltage (kV) Before	Voltage(kV) After	% Voltage Increase
Bus 2 (P. Tanglad)	18.12	19.03	5%
Bus 23 (P. Bunga Mekar)	18.14	19.05	5%
Bus 24 (P. Ceningan)	17.94	18.87	5%
Bus 26 (P. Karang Sari)	18.68	19.6	5%
Bus 28 (P. Ped)	17.92	18.84	5%
Bus 5 (P. Suana)	18.67	19.58	5%
Bus 33 (P. Lembongan)	18.08	19.0	5%

As shown in Table 16, the most significant improvement in voltage quality occurs under the PV–BESS configuration. The enhancement in voltage levels enables optimal power delivery from the generation sources to the load.

3.1.3 Computer-Based Power System Software Simulation

The simulation was carried out using the load supplied exclusively by the Indonesia Power Services (IPS) diesel generator, with an average load of 4,243 kW. As illustrated in Figure 12, the generation units connected to the AC bus include the PLTD and the converter, while the PV system and the BESS are connected to the DC bus. The simulation was conducted under two configuration scenarios:

- Diesel–PV–BESS
- PV–BESS only

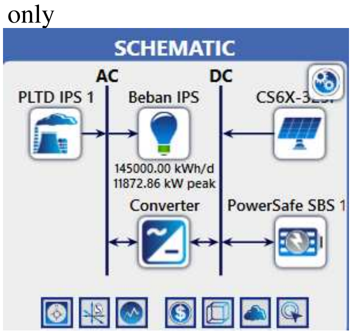

Figure 12. Hybrid Power Generation System Model in Nusa Penida Island

The proposed hybrid operational configuration integrates the diesel generator, photovoltaic (PV) system, and battery energy storage system (BESS). While the PV system incurs no fuel cost, it requires a high initial capital investment for the procurement and installation of solar panels. In this configuration, the generating units consist of a 6,000 kW PLTD operated by Indonesia Power Services (IPS), with an annual capacity shortage of 51,808 kWh. Based on the simulation results, the Levelized Cost of Energy (LCOE) was calculated at IDR 3,088. The simulation results are illustrated in Figure 13.

Simulation Results

System Architecture: EnerSys PowerSafe SBS 170F (16,649 strings)
CanadianSolar MaxPower CS6X-325P (20,629 kW) System Converter (6,085 kW)
PLTD IPS 1 (6,000 kW) HOMER Load Following

Total NPC: 2.54E+012
Levelized COE: Rp3,088.40
Operating Cost: Rp122,432,700,000.00

Production	kWh/yr
CanadianSolar MaxPower CS6X-325P	32,923,047
PLTD IPS 1	34,629,702
Total	67,552,749

Consumption	kWh/yr	%
AC Primary Load	52,906,513	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	52,906,513	100

Quantity	kWh/yr	%
Excess Electricity	13,608,270	20.1
Unmet Electric Load	18,487	0.0349
Capacity Shortage	51,808	0.0979

Quantity	Value	Units
Renewable Fraction	34.5	%
Max. Renew. Penetration	773	%

Figure 13. Simulation Result Operation Diesel-PLTS-BESS

A subsequent simulation was conducted for the standalone PV–BESS hybrid configuration. The results indicate that the system achieves an annual energy output of 52,855,427 kWh, with a capacity shortage of 52,694 kWh per year. The calculated Levelized Cost of Energy (LCOE) for this configuration is IDR 5,721, as depicted in Figure 14.

Simulation Results

System Architecture: System Converter (13,905 kW)
CanadianSolar MaxPower CS6X-325P (71,414 kW) HOMER Load Following
EnerSys PowerSafe SBS 170F (139,815 strings)

Total NPC: 4.71E+012
Levelized COE: Rp5,720.96
Operating Cost: Rp117,909,000,000.00

Production	kWh/yr
CanadianSolar MaxPower CS6X-325P	113,971,839
Total	113,971,839

Consumption	kWh/yr	%
AC Primary Load	52,885,467	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	52,885,467	100

Quantity	kWh/yr	%
Excess Electricity	57,414,426	50.4
Unmet Electric Load	39,533	0.0747
Capacity Shortage	52,694	0.0996

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	2,674	%

Figure 14. Simulation Result Operation PLTS-BESS

Table 17. LCOE Comparation

No.	Configuration	LCOE
1.	Diesel-PV-BESS	IDR 3,086
2.	PV-BESS	IDR 5,721

Based on Table 17, the PV–BESS hybrid configuration exhibits the highest LCOE value. Although this configuration does not require fuel for operation and incurs significantly lower operation and maintenance (O&M) costs compared to the Diesel–PV–BESS configuration, it involves a considerably higher capital investment, which directly contributes to the elevated LCOE.

In contrast, the Diesel–PV–BESS configuration demonstrates a lower LCOE and offers greater long-term stability, particularly due to its reduced dependence on fossil fuel price volatility. In this configuration, the BESS plays a critical role by storing excess energy generated from both the PV system and the diesel generators. This stored energy can be utilized during nighttime or periods of low solar irradiance, effectively reducing diesel fuel consumption and associated operational costs.

IV. CONCLUSION

Based on the results and analysis, several key conclusions can be drawn. First, the integration of a PV–BESS system is technically feasible and capable of meeting the energy demand in Nusa Penida Island, with a capacity of up to 14 MW. Second, the computer-based power system simulation indicates that in the base case configuration using only diesel generators, the feeder voltage ranged from 17.94 kV to 18.68 kV. When reconfigured into a hybrid generation system, voltage quality improved by approximately 4%, reaching a range of 18.73 kV to 19.49 kV. The most optimal voltage performance was observed under the standalone PV–BESS configuration, where voltage levels increased by 5%, ranging from 19.0 kV to 19.60 kV. Lastly, from a techno-economic perspective, the PV–BESS configuration resulted in a Levelized Cost of Energy (LCOE) of IDR 5,721. However, the most cost-effective and operationally stable configuration was the Diesel–PV–BESS hybrid, with a significantly lower LCOE of IDR 3,088, making it the most optimal solution in balancing investment cost, energy reliability, and long-term operational sustainability.

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