Optimal Sizing and Performance Assessment of a Hybrid Diesel and Photovoltaic with Battery Storage Limited by a Take-or-Pay Contract of Power Purchase Agreement in Nusa Penida Island, Indonesia

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Abstract- In remote and rural areas where diesel generators are usually employed for electricity production, Photovoltaic (PV) panels combined with Battery Energy Storage System (BESS) can lead affordable and reliable power generation. In this work, a real case study in Nusa Penida Island, Bali Province, Indonesia, is conducted for studying the optimal sizing and performance assessment of a hybrid diesel-PV-BESS system limited by a Take-or-Pay contract of Power Purchase Agreement (PPA). The island's solar irradiance is 5,36 kWh/m^2/day and 7 x 1.7 MW diesel power plant stations are currently run for fulfilling the island's electricity demand. The stations are embedded into an existing 20 kV distribution grid. Using the electricity demand projection of several representative days in a year, HOMER software is utilized in this work for designing and optimizing the size of PV and BESS integrated to the diesel power generators. In this study, the performance of configurations with four different sizes of PV and BESS are assessed using load flow analysis, short circuit analysis and transient stability analysis. The simulation results demonstrate that the optimal sizing of the hybrid system consists of 10 MWp PV and 10 MWh BESS with Levelized Cost of Energy of 9.45 cents USD/kWh. It lowers 40% of the current cost. Considering the initial, maintenance, replacement and fuel costs, the net present cost of the optimal configuration is 135,306,800 USD. This study confirms that the renewable energy penetration in remote and rural islands can be increased by optimally utilizing energy storage.

1. Introduction

Indonesia is the largest archipelago in the world with a total of 17,508 islands, among which 6,000 are inhabited. Today, a number of the islands in the country still have no electricity access. The generation of electrical power in remote and rural regions by connecting to the national grid is often not affordable. A common way to meet energy demand in those areas is by employing diesel generators for electricity production. However, due to the Government of Indonesia (GoI) ambitious targets of increasing the share of new and renewable energy in the national energy mix up to 23% in 2025 [1], the way shall be reconsidered.

Among the renewable energy technologies employed in decentralized applications, solar-based energy systems have the broadest utilization for generating electricity today [2]. Nevertheless, due to intermittent characteristic of renewable energy, the energy source alone is not able to generate electric power continuously at a capacity needed to satisfy the power demand. Applying hybrid technologies consisting of diesel generators and renewable energy sources with energy storage system can therefore lead affordable and reliable electricity generation in remote and rural areas.

In a hybrid diesel-renewable-energy storage system, optimal sizing and performance assessment are important facets of system design. Given a capacity of diesel power generator and electricity demand projection, this study aims obtaining the optimum capacities of Photovoltaic (PV) and Battery Energy Storage System (BESS) integrated to diesel power generators in order to ensure the electricity production quality and reliability of a remote and rural region. The configuration of the hybrid system is illustrated in Fig. 1.

A number of studies have been conducted to determine the optimal design of typical hybrid systems [3] - [18]. They are done by applying various algorithm and optimization software such as HOMER and Grey Wolf Optimizer [5]. To review of optimization research on hybrid energy systems, several strategies are employed, including: Levelized Cost of Energy (LCoE) [3] - [4], Net Present Cost (NPC) [8], cost analysis [4], cost of energy [9], standard economic analysis [10], and life cycle cost [11].

In view of the shortcomings of the existing literature, this paper is conducted for studying the optimal sizing and performance assessment of a hybrid diesel-PV-BESS system limited by a Take-or-Pay (ToP) contract of Power Purchase Agreement (PPA). In other words, the main novelty of our study lies on a special case study where the only contract type for power purchase agreement is the ToP contract.

The real case study is conducted in Nusa Penida Island, Bali Province, Indonesia. The island has a peak solar irradiance of 5.36 kWh/m^2/day and peak electricity demand of 7.25 MW mainly occurring on several days in June at around 7 p.m. The hybrid system is embedded into an existing 20 kV distribution grid. Given the optimal sizing of the hybrid system, we then assess and evaluate its performance using load flow, short circuit, transient, frequency and stability analysis, circuit clearing time and power quality.

We build five scenarios with different sizes of PV and BESS integrated to 7 x 1.7 MW diesel power generators. We combine LCoE and NPC analysis to review the scenarios in order to obtain an optimal configuration of the hybrid system implemented in Nusa Penida Island. Using seven (7) representative days, both during the day and night, in a year, Hybrid Optimization Model for Electric Renewable (HOMER) software is utilized in this work for designing, optimizing and assessing the performance of diesel, PV and BESS technologies.

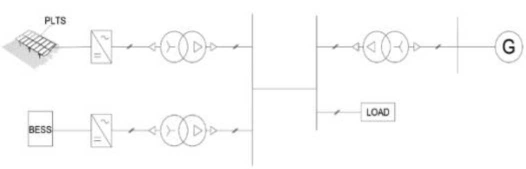


Fig. 1. A configuration of hybrid diesel-PV-BESS

The rest of this paper is structured as follows. Chapter 2 provides a comprehensive setting, methodology and data used in this study. Chapter 3 discusses the simulation results. Conclusion and further work are presented in Chapter 4.

2. Setting, Methodology and Data

2.1. Setting

Located on the equator, Nusa Penida Island is exposed to intense solar radiation throughout the year. Radiation increases steadily from January to April, reaching a peak at 5.36 kWh/m^2/day in April. It gradually decreases to 3.21 kWh/m^2/day at the lowest in December. The average daily solar irradiation per month in this region is presented in Fig. 2.

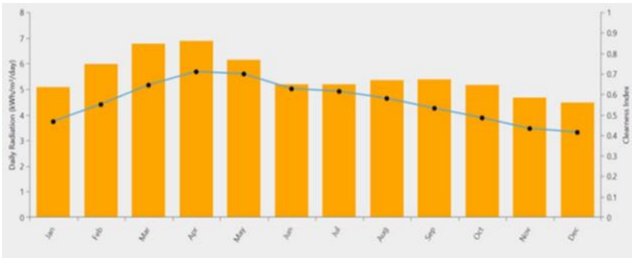


Fig. 2. Profile Irradiation of Nusa Penida [12]

In this paper study, four configurations of the hybrid system were selected in order to obtain the optimum combination of 7 x 1.7 MW diesel power plants, PV and BESS. The proposed configurations are shown in Table 1. We consider **Scenario 1** as a reference, where only the diesel power generators satisfy the power demand of the Nusa Penida Island.

The current holder of PPA for existing Scenario 1 is Cogindo, which is a subsidiary of PT Indonesia Power. The PPA obtained a ToP contract with PT PLN, which is a state-owned electricity company. In detail, the ToP contract has High Speed Diesel (HSD) 65% of the capable capacity of 6 MW. It implies that PT PLN guarantees 65% of the capable power capacity of 6 MW. In a case that the power generation is less than 65%, PT PLN needs to pay the minimum ToP contract. However, in a case that the power generation is lacking due to such an interruption, some fine is adjusted in the total payment. The Cogindo's diesel power generators currently have a temporary capacity of 7 x 1.5 MW, with a total maximum capacity of 7 x 1.7 MW diesel power plants. It implies that PT Cogindo has a back-up diesel power generator in the event of a blackout and maintenance simultaneously, which is about 7 x 0.2 MW. For all five scenarios proposed in Table 1, we assume that the diesel power generators have obtained a PPA with a ToP contract with PT PLN.

Table 1. Scenarios 1-5 for a hybrid diesel-PV-BESS

Scenario	Diesel power generator	PV	BESS
1	7 x 1.7 MW	-	No
2	7 x 1.7 MW	10 MWp	10 MWh
3	7 x 1.7 MW	10 MWp	7.5 MWh
4	7 x 1.7 MW	5 MWp	5 MWh
5	7 x 1.7 MW	5 MWp	2.5 MWh

2.2. Methodology and Data

In a hybrid diesel-renewable-energy storage system, optimal sizing and performance assessment are important facets of system design. To correctly examine the five scenarios proposed above, the following data and analysis framework are employed in this study:

- Site specification,
- Hybrid system model,
- Optimal sizing and performance assessment methods, and
- Data sets.

2.2.1. Site specification

Several renewable energy projects with different energy sources in Bali are shown in Fig. 3. As depicted in the figure, Nusa Penida Island is an island southeast of Bali, with a maximum altitude of 524 meter and area of 202.8 km^2. Compared to the majority of regions in Bali Province which is well known around the world for its forested volcanic mountains, iconic rice paddies, beaches and coral reefs, Nusa Penida Island has few tourist infrastructures and drier than the nearby islands in Bali. This study focuses on a diesel power plant in Kutampi Beach, Klungkung Regency, Nusa Penida Island. The PV plant studied in this work is located approximately 3.5 km from the diesel power plant.

Fig. 3. Several renewable energy projects making use of different energy sources in Bali, Indonesia [19]

2.2.2. Hybrid system model

Focusing on a diesel power plant with a total capacity of 7 x 1.7 MW in Kutampi Beach, this work aims at obtaining an optimum capacity of PV and BESS integrated into the diesel power plant. Currently, electricity demand in Nusa Penida system is supplied by the power plant and distributed through a 20 kV electricity grid. The grid operates radially and consists of single circuit, 150 mm^2 AAAC conductor overhead lines and MVTIC cable. Figure 4 illustrates the single line diagram of distribution system in Nusa Penida.

The schematic configuration of the hybrid diesel-PV-BESS proposed in this work is depicted in Fig. 1. The diesel power plant and PV panels are connected to AC buses, battery banks are placed at separate DC buses, and AC and DC buses are connected with each other through two-way AC/DC converters. Mono Crystalline Silicon PV with 27.648 modules, capacity of 10 MWp and annual production of 14.99 GWh per year are connected to the diesel power plant. The PV plant is located around 200 meters to the existing 20 kV electricity grid. The plant utilizes BESS manufactured by TESLA Powerpack Battery with a capacity of 10 MWh. In order to optimize and assess the performance of the proposed hybrid diesel-PV-BESS, we utilize HOMER software for designing the configuration.

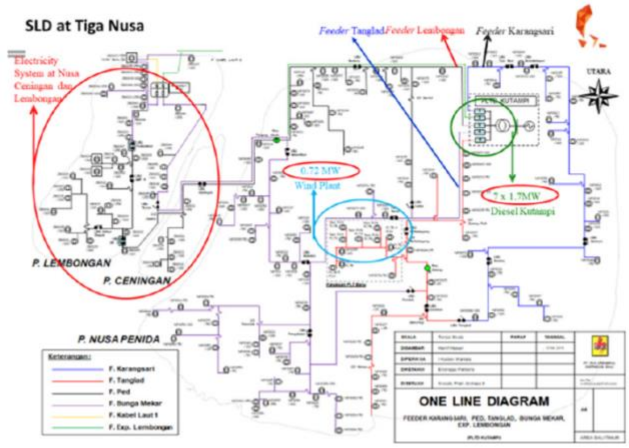


Fig. 4. Single line diagram of the 20 kV distribution grid in Nusa Penida Island [20]

2.3. Optimal Sizing and Performance Assessment Methods

2.3.1. Optimal Sizing Methods

We select an optimum configuration of the hybrid system among five scenarios based on NPC and LCoE. The NPC is defined as the present value of all costs associated with a system incurred over its lifetime, minus the present value of all revenues earned over its lifetime. The costs include capital costs, replacement cost, operation and maintenance costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue. The NPC is therefore mathematically calculated by following formula [20]:

$$\mathrm{NPC} = \frac{C_{\mathrm{cap}} + C_{\mathrm{rep}} + C_{\mathrm{O\&M}} + C_{other}}{\mathrm{CRF}}, \quad (1)$$

where C_{cap}, C_{rep}, $C_{\mathrm{O\&M}}$, C_{other} represent the capital costs, replacement cost, operation and maintenance costs, and other costs (fuel costs, emissions penalties, and the costs of buying power from the grid), respectively. And CRF determines the capital recovery factor, defined by [21]:

$$CRF = \frac{i(1+i)(1+i)^N}{(1+i)^N - 1}$$

where i is the real annual interest rate and N is the number of year.

LCOE defines the average cost per kWh of useful electrical energy produced by the system, which is given by [18]:

$$\mathrm{LCoE} = \frac{C_{ann,tot} - c_{\mathrm{boiler}} H_{\mathrm{served}}}{E_{served}}, \quad (2)$$

where $C_{ann;tot}$, c_{boiler}, H_{served}, E_{served} define total annualized cost of the system, boiler marginal cost, total thermal load served, and total electrical load served, respectively.

2.3.2. Performance Assessment Methods

In this study, the performance of configurations with four different sizes of PV and BESS is assessed and evaluated using load flow analysis, short circuit analysis and transient stability analysis.

The load flow analysis is here conducted to analyze active and reactive power flow, voltage levels at each substation, power plant, distribution network, network load, and system losses. The load flow analysis is done under a normal condition, where all distribution networks in the Nusa Penida system are in the condition of serving load requests. This normal condition is carried out for load flow analysis in two scenarios, which are before and after the Nusa Penida hybrid system operating at day and night-time loads.

Short circuit analysis is performed to determine a breaking capacity of a circuit breaker at a substation. Based on network configuration, the level of short circuit current in each substation is analyzed by placing 3-phase short circuit interruption to each substation. The 3-phase interference is used to get the maximum level of short circuit (at the worst case) that occurs at the substation. We will analysis the different between the short circuit levels in the Nusa Penida system before and after the hybrid diesel-PV-BESS is operating.

The objective of transient stability analysis is to analyze the system performance in case of a disturbance case in the Nusa Penida system. Loss of load due to changes in irradiation, disruption of generation and losses in the distribution network system is simulated to determine the performance impact. This transient stability analysis is only focused on the impact of the operation of the hybrid diesel-PV-BESS under day-time load conditions.

2.4. Data Sets

The peak load of the Nusa Penida power system is around 7.25 MW, generally occurred in several days in June at 7 p.m. The average load during a day is approximately 5.54 MW. The estimated difference in load between day and night is 1.71 MW. When the PV plant is estimated to operate, the peak load and average daytime loads are around 8.05 MW and 6.09 MW, respectively. The typical hourly load curves in the Nusa Penida power system in 2018 and 2019 are shown in Fig. 5. Due to trends in energy sales, regional economies, and economic and population growth in Nusa Penida Island, it is projected that the average peak load, energy sales and energy production per year for the upcoming 7 years are 11.1 MW, 11.5 GWh and 11.4 GWh, respectively.

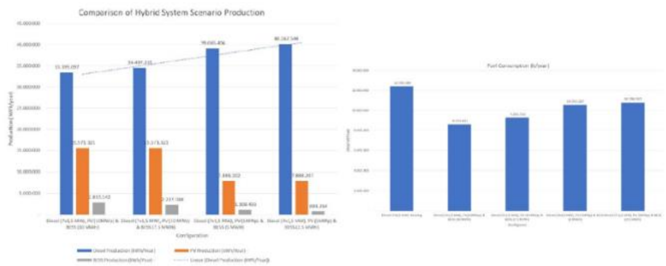


Fig. 5. Production comparison and fuel consumption comparison of the proposed configurations of the hybrid system

As described in Section 2.1, we build five scenarios to search for an optimum capacity of the hybrid generation system. The economical parameters and lifetime of the diesel power generators, PV and BESS utilized are shown in Table 2. Furthermore, the de-rating factor, temperature coefficient of power, nominal operating cell temperature, and efficient at standard test conditions are 79%, -0.5%, 47, and 13%, respectively. In addition, the minimum load ratios of diesel power generator and ion-BESS utilized in this study are 60 and 10%, respectively.

3. Results and Discussion

Here we show the simulation results of optimal sizing and performance assessment of the hybrid diesel-PV-BESS being implemented in Nusa Penida Island. As stated in Section 2.3.1, an optimum configuration of the hybrid system among five scenarios is selected based on NPC and LCoE, whereas the performance assessment is done by studying the load flow analysis, short circuit analysis and transient stability analysis of the optimum scenario. The HOMER software is utilized in this work for providing simulation results of both optimal sizing and performance assessment of the hybrid diesel-PV-BESS.

3.1. Optimal sizing of the proposed hybrid system scenarios

3.1.1. Diesel power generator as a baseline scenario

This scenario is simulated based on the existing diesel power generator using the available data up to 2019. This aims for accurately analyze the impact of integrating PV and BESS into the power generation system on NPC, LCoE, fuel consumption, and other technical characteristics. In particular, this scenario is based on the Kutampi Nusa Penida Diesel Generator, having a ToP contract of PPA.

The initial capital cost, replacement cost, operation and maintenance cost and lifetime of this baseline scenario are presented in Table 2. The LCoE and NPC calculated using HOMER software are, respectively, 15 cent $/kW and 189,429,520 USD. With a fuel efficiency of 100 %, the annual fuel consumption is 12,390,385 liters, whereas the diesel production level is as 46,550,028 kWh/year.

Table 2. The economical parameters and lifetime of the diesel power generators, PV and BESS utilized.

Component	Initial capital cost	Replacement cost	Operation and maintenance cost	Lifetime
Diesel generator	24.54 $/kW	24.54 $/kW	0.01142 $/kW	90.000 hours
PV	760 $/kW	152 $/kW	7.6 $/kW	25 years
BESS (and converter)	400 $/kW	90 $/kW	1260 $/year	10 years

3.1.2. Hybrid diesel-PV-BESS

As mentioned earlier, we build four scenarios (Scenario 2-5) shown in Table 1. We aim to obtain some insights when the proposed scenarios of the hybrid diesel-PV-BESS only have a ToP contract of PPA with a portion of 16.67%. The ToP contract of PPA diesel generation reduced by PV and BESS of Scenario 2-5 are 16.67%. The renewable energy portions of Scenario 2-5 are 21.31%, 21.31%, 2.57%, and 2.57%, respectively.

The initial capital cost, replacement cost, operation and maintenance cost and lifetime of PV and BESS are shown in Table 2. The production comparison and fuel consumption comparison of the proposed four scenarios are presented in Fig. 5. The LCoE and NPC values of the scenarios can be found in Fig. 6. From the figure and Section 3.1.1, it is concluded that Scenario 2 provides the lowest LCoE and NPC among other scenarios, which are 12.68 cent USD/kWh and

135,306,800 USD, respectively. The optimum sizing of the hybrid system is therefore when the PV and BESS both have a capacity of 10 MW.

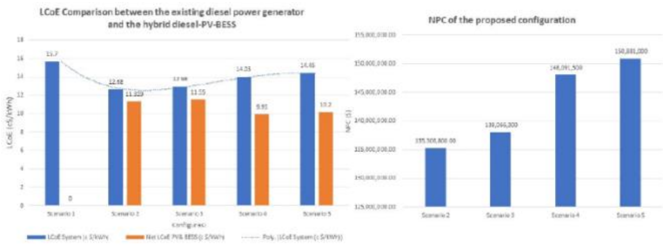


Fig. 6. LCoE and NPC comparison of the proposed configurations of the hybrid system

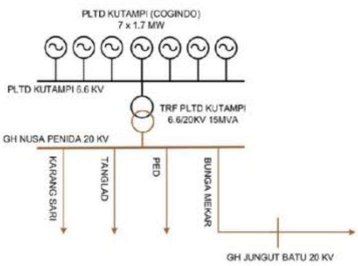
3.2. Performance assessment of the hybrid power plant system

The intermittent characteristic of solar energy using PV technologies is particularly due to solar irradiation, which depends on location, season, day/night time, and cloud cover. When the variability of the solar energy output in the integration system is less than 10% of the total grid power, some back-up energy is necessary to be there in the system. However, in a case that the variability of the solar energy output in the integration system excess in a range of 10-15% of the total grid power (high penetration of solar power plant), changes in the operating system are compulsory to be done. It is therefore important to utilize a BESS when integrating PV into diesel power generator.

3.2.1. Load flow analysis

As described before, we conduct the load flow analysis to assess the active and reactive power flow, voltage levels at each substation, power plant, distribution network, network load, and system losses. The load flow analysis is done under a normal condition, where all distribution networks in the Nusa Penida system are in the condition of serving load requests. This normal condition is carried out for load flow analysis in two scenarios, which are before and after the Nusa Penida hybrid system operating at day and night-time loads.

From the table shown in Fig. 7, the voltage profile for all scenarios is still within the acceptable voltage range. Moreover, the operation of the hybrid diesel-PV system increases the voltage profile. The results of the load flow analysis indicate that there is no distribution network load exceeding the current capacity.



Voltage Profile Before and After PV Operation

Substation	Voltage Profile (kV)			
	Daylight Load		Day Night Load	
	Before	After	Before	After
PLTD Cogindo #1-7 (6.6 kV)	6.6	6.6	6.6	6.6
PLTD Kutampi (20 kV)	19.6	20.1	19.5	19.7
PV Nusa Penida (20 kV)	19.6	20.3	19.5	19.8
NP0062/160 (Feeder Karangsari)	19.6	20.1	19.5	19.8
NP0002/100 (Feeder Ped)	19.5	20.0	19.4	19.6
NP0109/100 (Feeder Bunga Mekar)	19.6	20.1	19.5	19.6
NP0007/100 (Feeder Tanglad)	19.6	20.1	19.5	19.8

Fig. 7. Single line diagram of Nusa Penida Distribution System (left) and voltage profile before and after PV operation (left). PLTD refers to the diesel power generation plant.

3.2.2. Short circuit analysis

As mentioned earlier, we perform the short circuit analysis to determine a breaking capacity of a circuit breaker at a substation. Based on network configuration, the level of short circuit current in each substation is analyzed by placing 3-phase short circuit interruption to each substation. The 3-phase interference is used to get the maximum level of short circuit (at the worst case) that occurs at the substation. We will analysis the different between the short circuit levels in the Nusa Penida system before and after the hybrid diesel-PV-BESS is operating.

Figure 8 shows that there is no breaking current (ib) exceeding its rating (16 kA or 24 kA in a 20 kV system). As also shown in the figure, generally all substations have lower break current (Ib) after the hybrid plant operates. This is due to the fact that a number of diesel generators are turned off or in a standby mode.

Nusa Penida Short Circuit Level

Substation	Short Circuit (kA)											
	Daylight Load						Day Night Load					
	Before			After			Before			After		
	ik"	ip	ib	ik"	ip	ib	ik"	ip	ib	ik"	ip	ib
PLTD Cogindo #1-7 (6.6 kV)	4.75	12.19	3.75	2.28	5.18	2.00	5.54	14.22	4.38	4.77	12.48	3.77
PLTD Kutampi (20 kV)	1.21	3.28	1.08	0.69	1.56	0.63	1.36	3.69	1.23	1.22	3.25	1.08
PV Nusa Penida (20 kV)	1.16	2.91	1.05	0.70	1.52	0.64	1.30	3.23	1.19	1.17	2.89	1.06
NP0062/160 (Feeder Karangsari)	1.17	3.08	1.05	0.68	1.51	0.62	1.31	3.44	1.19	1.17	3.05	1.06
NP0002/100 (Feeder Ped)	1.17	3.08	1.05	0.68	1.51	0.62	1.31	3.44	1.19	1.17	3.05	1.06
NP0109/100 (Feeder Bunga Mekar)	1.19	3.16	1.06	0.68	1.53	0.62	1.33	3.54	1.21	1.19	3.13	1.07
NP0007/100 (Feeder Tanglad)	1.14	2.96	1.04	0.67	1.48	0.612	1.28	3.29	1.17	1.15	2.93	1.04
Bus 1 (0.4 kV)	NA	NA	NA	22.93	52.29	22.53	NA	NA	NA	NA	NA	NA
Bus 2 (0.4 kV)	NA	NA	NA	22.93	52.29	22.53	NA	NA	NA	NA	NA	NA
Bus 3 (0.4 kV)	NA	NA	NA	22.93	52.29	22.53	NA	NA	NA	NA	NA	NA
Bus 4 (0.4 kV)	NA	NA	NA	22.93	52.29	22.53	NA	NA	NA	NA	NA	NA

Fig. 8. Nusa Penida short circuit level, with day and night-time loads. PLTD refers to the diesel power generation plant

3.2.3. Transient stability analysis

To analyze the system performance in case of a disturbance case in the Nusa Penida system, we conduct a transient stability analysis. We simulate loss of load due to changes in irradiation, disruption of generation and losses in the distribution network system to determine the performance impact. In this study, the transient stability analysis is focused on the impact of the operation of the hybrid diesel-PV-BESS under daylight load conditions.

Case 1: *Simulation of a hybrid PV output system with solar irradiation changes*

Based on a realistic pattern of PV production, the biggest drop of the energy production is when solar irradiation changes from 1 kW/m^2 to 0.75 kW/m^2 (25% changes) within 10 minutes. The transient stability simulation is done in this study to determine the impact of losses due to 25% reduction of solar energy production within 10 minutes in the Nusa Penida system.

The pattern presented in Fig. 9a shows the active power output from **PV-3 and PV-4** bus due to 25% irradiation change within 10 minutes. Irradiation change begins at t = 16.67 second and ends at t = 600 second. As explained before, when irradiation starts to change, the charging of BESS will stop soon. This means that the Nusa Penida system will experience loss of load around 2.5 MW at t = 16.67 second.

Also, from the figure, at time *t* = 8.33 seconds the output of PV-3 and PV-4 decreases from 1.784 MW to around 1.225 MW to balance between energy supply and demand in the system. Gradually, the output of PV-3 and PV-4 increases with the reduction of solar irradiation up to *t* = 600 seconds, irradiation change ends.

The pattern on Fig. 9b shows a system frequency at bus PV Nusa Penida as a point of common coupling (PCC) between Nusa Penida system and Solar PV Power Plant. It is also important to note from the figure that system frequency is relatively stable at 50 Hz during the change of solar irradiation. The stable frequency is due to existence of BESS.

Case 2: *Simulation of short circuit in feeder 20 kV – Feeder Ped*

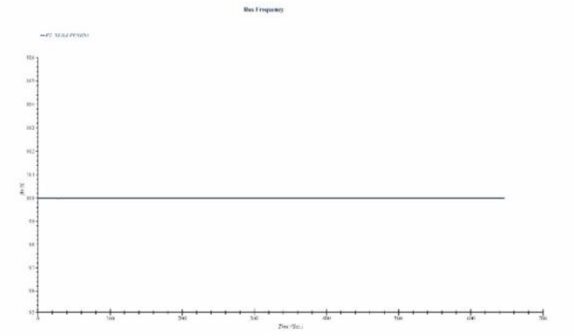
In this simulation, 3-phase fault occurs at the beginning of Feeder Ped during 350 milliseconds and the fault is cleared by opening circuit breaker of Feeder Ped. The pattern on Fig. 9c shows system frequency at bus PV Nusa Penida 20 kV.

Case 3: *Simulation of short circuit in feeder 20 kV – Feeder Bunga Mekar*

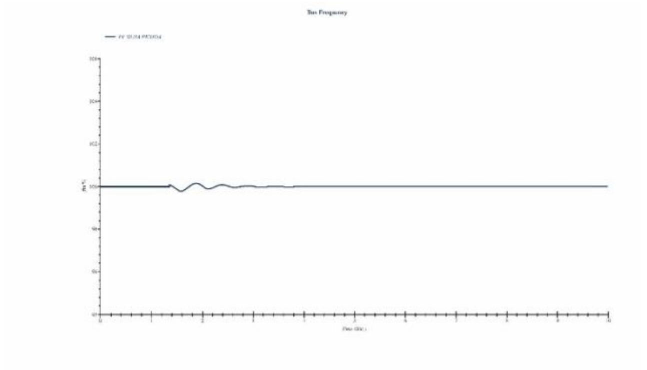
In this simulation, Feeder Bunga Mekar is suddenly outage due to mal-operation of Feeder Bunga's circuit breaker, resulting in a loss of load around 1.71 MW in the Nusa Penida system. The pattern on Fig. 9d shows the system frequency at bus PV Nusa Penida 20 kV.

Case 4: *Simulation of Feeder PV BESS*

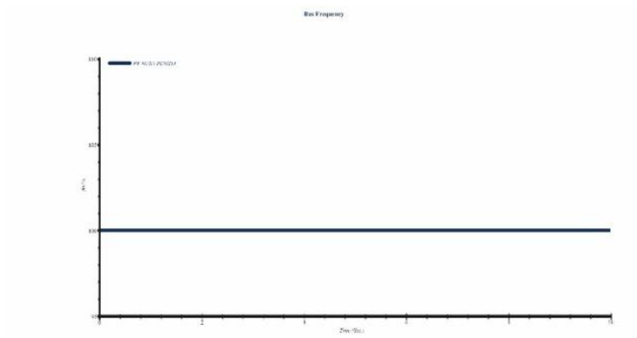
In this case, the simulation is done when outage occurs at Feeder PV BESS to substation. Figure 10 shows the system frequency at bus PV Nusa Penida 20 kV. The system frequency within 10 seconds drops from 100% (50 Hz) to 32% (16 Hz), resulting in total blackout/collapse system. A load shedding scheme may be implemented to avoid such an unexpected moment.



b. System frequency at bus PV Nusa Penida 20 kV – Case 1

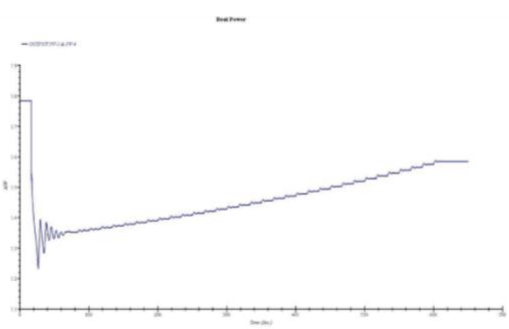


c. System frequency at bus PV Nusa Penida 20 kV – Case 2



d. System frequency at bus PV Nusa Penida 20 kV – Case 3

Fig. 9. Active power output for PV-3 and PV-4 due to irradiation change in Case 1 and system frequency at bus PV Nusa Penida 20 kV in Cases 1-3.



a. Active power output for PV-3 and 4 due to irradiation change – Case 1

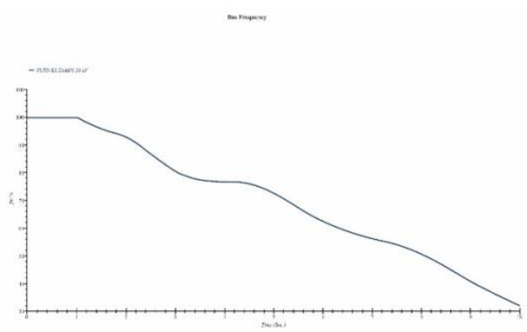


Fig. 10. Active power output for PV-3 and PV-4 due to irradiation change for Case 1 and system frequency at bus PV Nusa Penida 20 kV for Cases 1-3.

4. Conclusion

Among the baseline scenario and four proposed scenarios of the hybrid diesel-PV-BESS, PV with 10 MWp with Mono-Si module and 10 MWh BESS is the optimum configuration integrated the existing diesel power generators. The LCoE of the combination between PV and BESS is 9.45 cent USD/kWh. After embedded into the existing diesel power plant, the LCoE turns to 12.68 cent USD/kWh, which is the lowest LCoE among the scenarios. The NPC of combining the 10 MWp PV, 10 MWh BESS, and existing diesel power plant is 135,306,800 USD.

However, it is confirmed from our simulation results that the penetration of the PV and BESS leads to a reduction of the ToP diesel generator obligations, implying some consideration without amending the PPA. The most practical choice for considering it is to calculate the ABD component of the diesel generator and to be charged to the LCoE of the PV and BESS. The LCoE of 10 MWp PV and 10 MWh BESS increases from 9.45 cent USD/kWh to 11.32 cent USD/kWh.

The performance assessment through load flow analysis shows that with the integration of PV and BESS can improve the voltage level in daytime load conditions in the existing distribution network. The short circuit analysis proves that the short-circuit current is within the capacity range of the distribution substation. From transient stability analysis, it is concluded that irradiation changes and interference in one of the feeders (which are defined as disturbances), can still be well covered by BESS. The hybrid system will collapse blackout when there occurs interference in the PV feeder and BESS system. This unexpected moment occurs due to the fact that the engine requires start-up time to ramp up to 90% of the capacity. Another way to avoid black out is to divide the location of the PV plant in two different areas with each feeder implements a load shedding scheme.

Our simulations are based on the several representative days of electricity demand in Nusa Penida, Indonesia. Future research may use the projection of the electricity demand for the whole year to gather better analysis of the optimum sizing of a hybrid diesel and PV with BESS limited with a ToP contract of PPA. Recommendations for future research may also be to perform similar research in other islands in Indonesia with different demand profiles, different storage configurations, and other types of contract of PPA. This may yield valuable new insights for optimal sizing and performance assessment of the hybrid system.

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