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Design and analysis of a smart microgrid for a small island in Indonesia

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Abstract

Indonesia as the largest archipelago in the world has a big challenge to electrify all the inhabited islands due to the geographical dispersion. Microgrid development is one of the most suitable solutions in electrifying the islands while maximizing the utilization of renewable energy sources. In this paper a smart microgrid for a specific island in Indonesia, the Tidung Island, is designed and the challenges and benefits, cost and performance are analyzed.
The designed smart microgrid includes diesel generators, solar PV and battery storage systems. Different design options, without and with peak load shaving are considered and compared against each other. The peak load shaving is implemented using Energy Storage System (ESS) and Demand Response (DR). MATLAB/SIMULINK simulation results are used to investigate and compare the performance of the proposed designs. In addition, a cost and benefit analysis (CBA) is also carried out to give an approximate cost indication of the three different designs.

Keywords: Smart grid, microgrid, renewable energy, Indonesia, island

1. Introduction

Indonesia's power plant capacity in 2016 reached 57.1 GW with 258.58 million populations [1]. Although most of the electricity relies on domestic coal, Indonesia has started to add more renewable energy sources. Indonesia's target for renewable energy share in the energy mix is 23% by 2025, and 31% by 2050, which is in line with the Paris climate agreement target [2]. Moreover, Indonesia has quite a high potential for renewable energy, especially solar, wind, hydro, and geothermal. However, the renewable energy potential in Indonesia has not been optimally developed due to several reasons, like the high cost to invest, low efficiency of renewable generation, geographical location and social factors.

The smart grid technology can be used not only as an enabler for renewable energy development but also to make a better usage for the existing grid infrastructure. One path to start the smart grid development is to develop a smart grid from a microgrid level. A microgrid has almost all of the large grid components – generation, energy storage and distribution – but at a much smaller scale and it can operate independently. In other word, a smart microgrid for a small area can be developed with significant lower cost and complexity than for a large area.

Several countries have initiated island microgrid projects in the world [3]-[5]. Indonesia has successfully developed two operating pilot smart microgrid projects in Sumba and Nusa Penida islands. The Nusa Penida smart microgrid system has 11 diesel engines installed in 2005 with capacity of 5 MW and include 60 kW solar PV systems as well as a 720 kW wind power system [6]. The second smart microgrid project, the Sumba Island smart microgrid, was installed in 2012. It consists of 500 kW PV system, two smart generators of 135 kVA each, vanadium redox battery bank of 2x240 kWh, and sub-system control and data communication [7].

Many researchers have done numerous studies on smart microgrids. Some of them have made some

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studies about the benefits and challenges of smart microgrids [8]-[10]. Others have researched smart microgrid technologies such as Advanced metering infrastructure (AMI) [11], the demand response with renewable energy resources [12], and also the energy management [13].

There are a few number of researches about smart grid development in Indonesia [14], [15]. However, none of them developed a model for the designed smart microgrid for an island in Indonesia and investigated the performance of the designed system based on the simulation results at different operating conditions. This paper presents a smart microgrid design for Tidung Island based on real data and analyses the designed system performance using simulation results in MATLAB/Simulink environment.

2. Proposed Methodology for the Smart Microgrid Design and Analysis

Fig. 1 shows a flowchart of the proposed methodology for the design and analysis of the smart grid for a selected island. The island should be grid connected, with reasonably high residents and renewable energy generation capacity. In design, both energy storage and generation including conventional and renewable generators with suitable capacity should be considered. An appropriate model based on the designed system will be then developed to be used to investigate the system performance at different operating conditions. The design will be revised if the performance is not satisfactory.

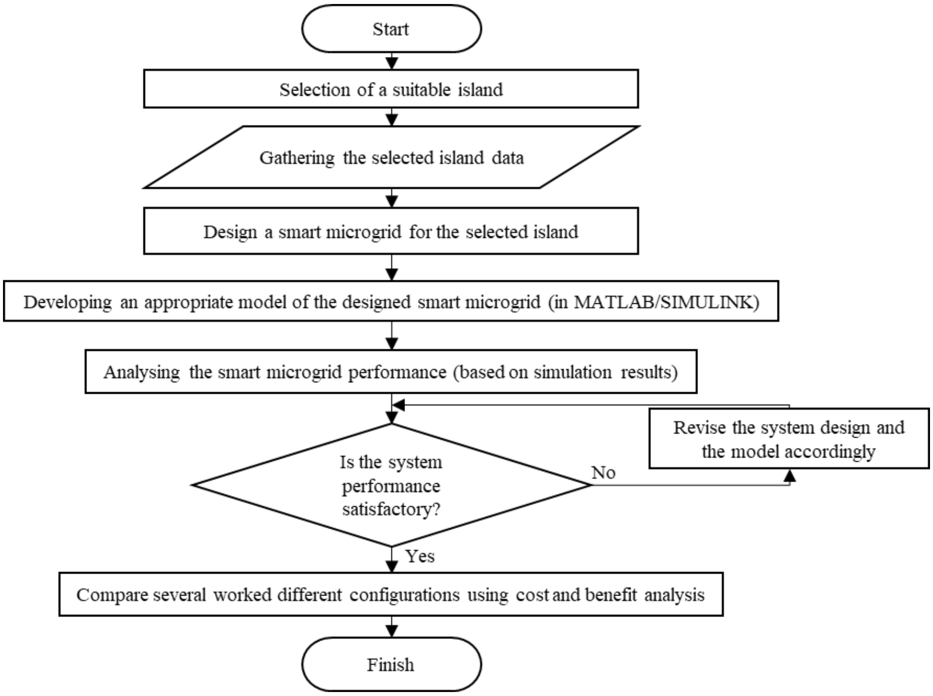

Fig. 1. Smart Microgrid Design and Analysis Workflow

3. Microgrid Design for Selected Island

Tidung Island is selected because of its location and number of habitants. It is located near the capital city of Indonesia and has already connected to the Java-Bali grid since 2012. The island population is 4,148 and it is considered as a high potential tourism destination, as 254,043 tourists in 2017 [16].

The island has a high renewable solar energy potential. The yearly average of solar irradiance in Tidung Island is 5.08 kWh/m2.day, while the average wind speed is much lower at 3.78 m/s [17] which makes the wind turbine development is not economically beneficial for this island.

A simplified single line diagram of the electricity connection from the main island to Tidung Island is shown in Fig. 2.

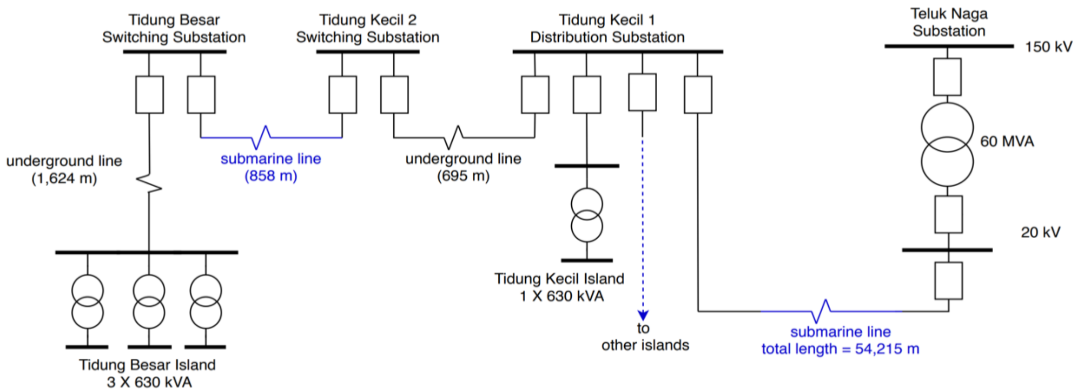

Fig. 2. Simplified single line diagram of Tidung island (adapted from [18])

Tidung Island's maximum peak load reaches 1.15 MW [19]. Assuming the electricity annual growth is 1.4% and the lifespan of the microgrid system can reach 25 years, the peak load after 25 years will be up to 1.67 MW. The proposed Distributed Generation (DG) units are PV system and diesel generator. The PV system is selected to utilise the solar radiation potential in the island, while the diesel generator is used for handling the load swings from the solar intermittency. For the storage, lithium-ion battery is selected because it is the most popular grid battery storage in the current market [20]. The overall generation and storage should meet the maximum load considering losses and anticipated growth. To support the renewable energy target of the government, the PV system is determined at 520 kWp which has portion at 26% of the overall generation. At this renewable penetration level, smart grid technology is highly required to allow reliable grid operation [21]. The summary of the customized initial size of the smart microgrid for Tidung Island is presented in Table 1.

Table 1. Tidung Island microgrid initial sizing

No	Component	Configuration	Total Rating
1	Diesel generator	2 × 750 kVA	1.5 MVA
2	PV system	520 kWp	520 kWp
3	Li-ion battery storage	500 kW / 1 MWh	500 kW / 1 MWh
Total Power Rating including the battery			2.52 MW

4. Simulation Study

4.1. System model

The model of smart microgrid system for Tidung Island was developed in MATLAB/Simulink environment as shown in Fig. 3.

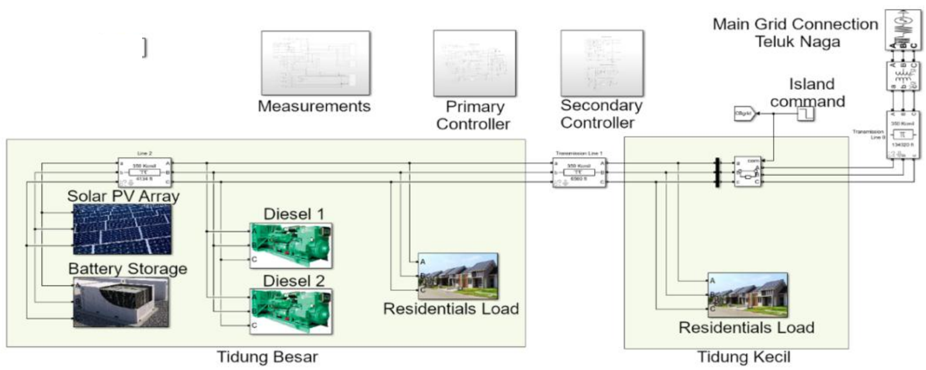

Fig. 3. Simulink model of Tidung island smart microgrid

4.2. Steady-state and transient analysis of the system without peak load shaving

The performance of the designed microgrid system without peak load shaving has been investigated at different operating conditions including the followings:

- Grid-connected mode
- Islanded mode
- Transition from grid-connected to islanded mode when the load is low following a fault
- The same transition but at a peak load time

Due to space limitation, only the results of two most important and severe operating modes, the full islanded mode and the last one, are reported here. Fig. 4 displays the simulation results only of the battery SOC, active and reactive powers from each microgrid component when the system is in full islanded mode. It is seen that at the beginning of the day, the power is supplied by the battery for about 30 minutes. Afterwards, the active and reactive powers are supplied by diesel generators and solar PV while the battery balances out the intermittent generated power from PV. The battery lefts 42.78% capacity at the end of the day.

It can be seen that in islanded mode, the microgrid successfully supplies the required active and reactive powers for the system for the whole day.

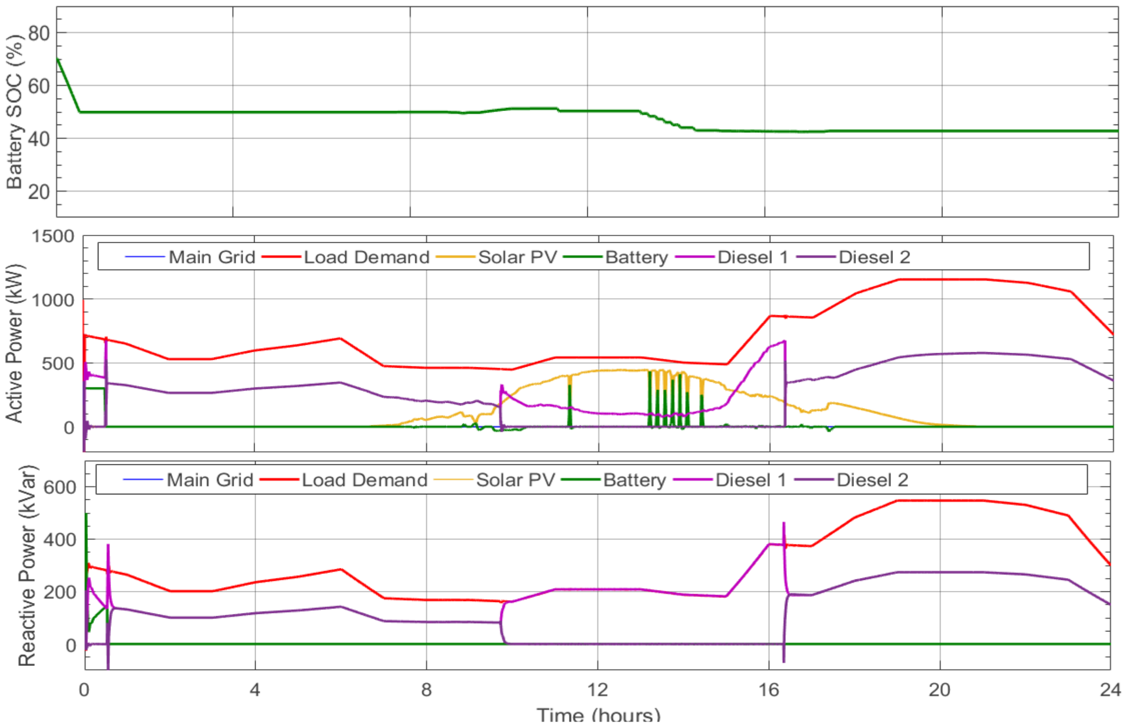

Fig. 4. Microgrid performance simulation results in the islanded mode scenario

Fig. 5 shows the simulation results when the system transits from grid-connected to islanded mode when a fault is happened at 8pm. It is seen that the designed microgrid system is stable before, during and after this severe fault and maintain the system frequency and voltage and the battery SOC within the recommended national/international limits. During transition time, the frequency drops to 48.36 Hz and rises to 50.59 Hz which is still within the recommended national grid code; 47.5Hz-52Hz [22]. The voltage swings between 16.54 kV (0.83 pu) and 22.28 kV (1.11 pu) but gets back soon to its nominal value in less than one second. The national grid code does not regulate the voltage limitation in transient state. However, the voltage swings are still within the IEEE 1547 and PRC-024-1 standard [23].

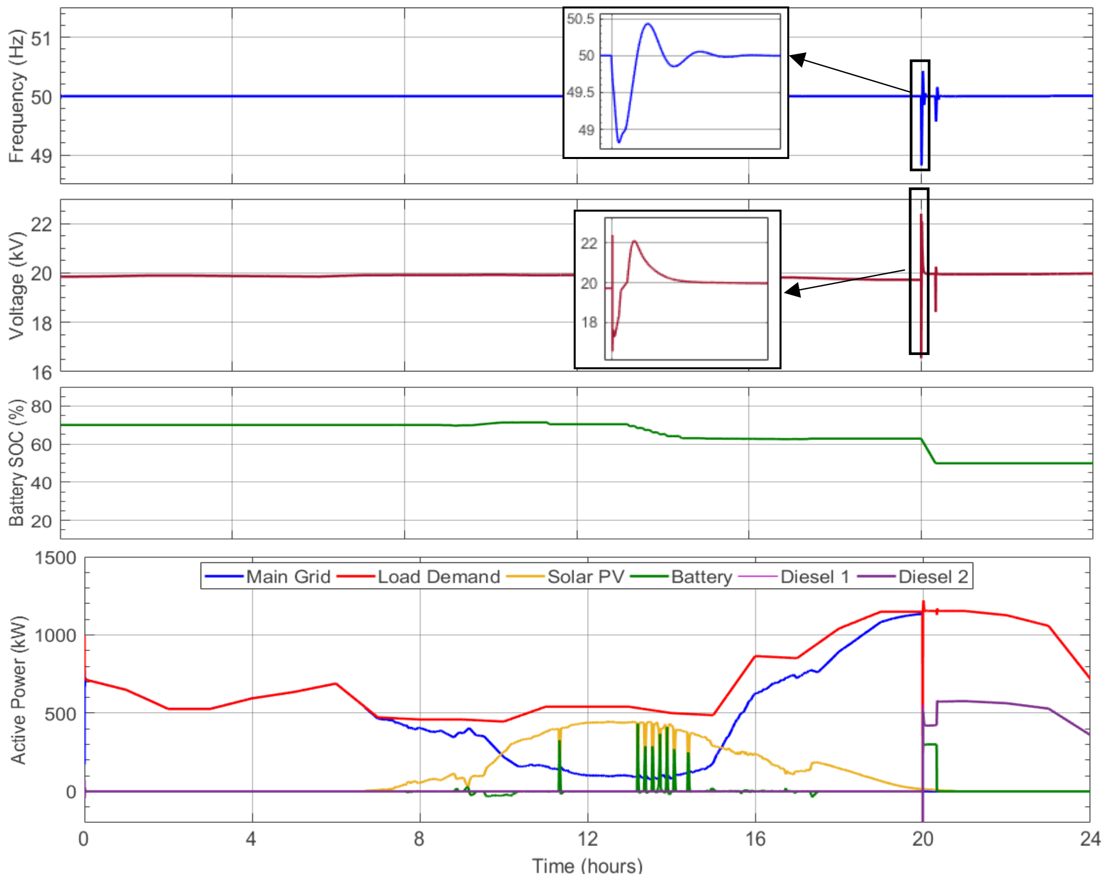

Fig. 5. Microgrid performance simulation results in the last scenario

The solar power fluctuation between 11am and 3pm represents the intermittency. It is seen that the battery compensates this intermittency and supplies the required power. The battery state of charge (SOC) is reduced first during the PV intermittency and drops when the system transits to islanded mode. However, when its SOC is reached 50%, the controller turns on the diesel generator to supply the power in islanded mode and to keep the battery SOC above 50% for emergency uses.

From the simulation results, it can be concluded that the designed system works well with satisfactory performance in both normal and contingency conditions. However, it is seen that the solar PV penetration generates high swing on the main grid load profile. This load pattern swing can be mitigated by implementing a peak shaving method to the microgrid system.

4.3. System with peak load shaving

Peak load shaving capability is added to the smart microgrid system mainly to improve the load pattern profile. It also can help the microgrid to provide power longer in islanded mode. Two common methods for peak load shaving have been investigated; 1) Energy Storage System (ESS) and 2) Demand Response (DR).

The peak load shaving using ESS is based on correct size of the battery storage. The peak load limit is determined to be 800 kW. To maximise the li-ion battery lifetime while performing peak load shaving every day, the battery SOC is kept between 45%-75% [24]. The peak load shaving should maintain the peak load level at the same as the current level after system life span which is assumed to be 25 years. After several simulation attempts, the minimum battery capacity is selected as 7,400 kWh for a low load limit of 540 kW. Fig. 6 illustrates the results with peak shaving using ESS with 7,400 kWh battery storage.

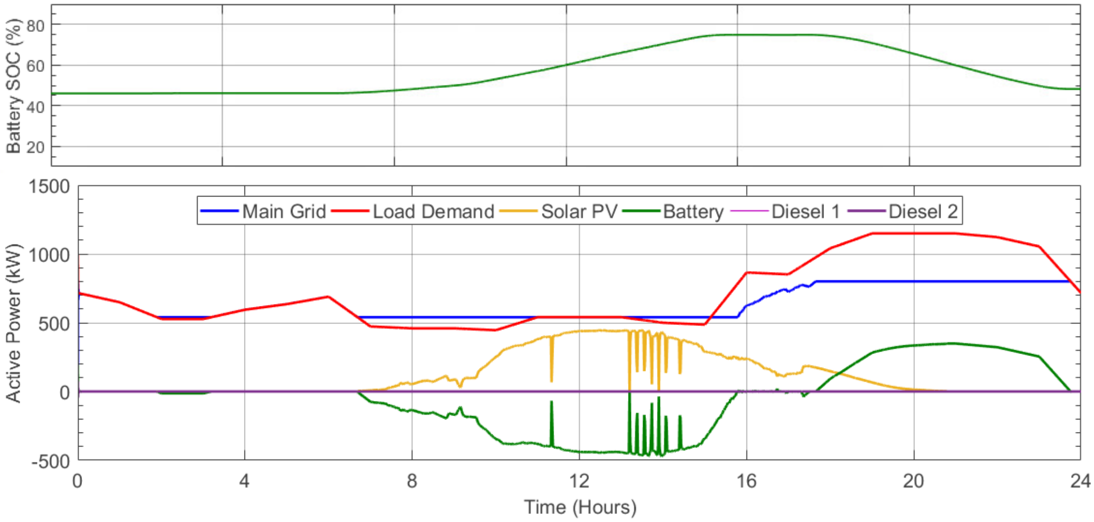

Fig. 6. Simulation result of peak shaving using ESS with 7,400 kWh battery

It is seen that the battery with the capacity of 7,400 kWh is enough to minimize the load pattern swing due to the solar PV intermittency. The battery SOC is 46% at the beginning and then increases up to 74.85% by absorbing the energy from the PV system while the minimum power from the main grid is kept at 540 kW. At peak load session, the battery discharges its capacity to lower the peak power from the main grid to 800 kW. So, the power swing from the main grid is reduced to 540 kW-800 kW which much lower than the range of the system without peak load shaving which is 82 kW-1149 kW as is shown in Fig. 5. The battery SOC remains 48.2% at the end of the day. As a conclusion, the peak load shaving by using a large battery shows promising results.

Demand Response (DR) method is an alternative method for a peak load shaving. The microgrid system uses some smart appliances to implement the DR which needs participation from consumers. The main barrier of demand response is the reluctance of the consumers to participate and support the grid. Several pilot projects in the US shows that the maximum consumer participation can only reach 36% residence participation [25]. Therefore, a demand response participant of 30% is assumed for Tidung Island. Fig. 7 shows the simulation result of the designed smart microgrid with DR peak load shaving.

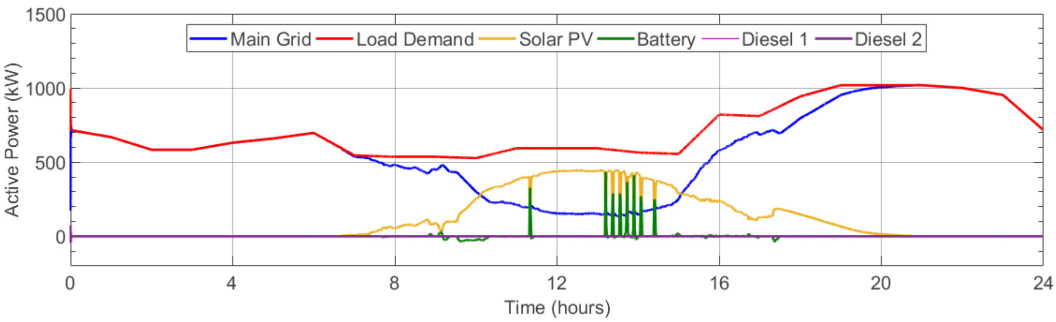

Fig. 7. Simulation results of DR peak load shaving at 30% participants

It is seen that the peak load shaving using DR with 30% consumer participation reduces the main grid load pattern fluctuation the range of 143 kW and 1,019 kW which is slightly smother than the results without peak load shaving (Fig. 5). A smother load pattern could be achieved if the consumers contribute more. Since this technique cannot utilise the power generated from PV at the day, the load pattern swing correction is much smaller compared to peak load shaving using ESS.

5. Financial Cost and Benefit Analysis

The total costs and benefits in this study are calculated for the whole microgrid lifespan which is 25 years. They are calculated by using Net Present Value (NPV) analysis by considering the discount rate at 6% which is close to the actual Indonesia interest rate. Table 2 summaries the results of the costs and benefits analysis (CBA) of the three proposed microgrid design options.

Table 2. Summary of CBA for the three proposed microgrid designs

Items	Without peak load shaving	With peak load shaving using ESS	With peak load shaving using DR
Capital cost	$ 2,868,380	$ 4,272,860	$ 2,919,032
Replacement cost	$ 62,444	$ 345,516	$ 62,444
Operation and Maintenance cost	$ 375,575	$ 989,176	$ 375,575
Imported electricity reduction benefit	- $ 1,195,574	- $ 1,195,574	- $ 1,195,574
GHG emission reduction benefit	- $ 437,802	- $ 437,802	- $ 437,802
Peak load shaving benefit	$ 0	- $ 312,222	- $ 137,566
Avoided upgrading cost benefit	$ 0	$ 0	$ 0
Resilience benefit	- $ 486,184	- $ 495,046	- $ 486,184
Total Net Cost-Benefit	**$ 1,186,838**	**$ 3,166,908**	**$ 1,099,924**

According to the CBA results, the cost of the system with peak shaving using DR is the lowest. Therefore, it would be a promising choice to build a system with a DR peak load shaving. However, suitable incentives need to be introduced to attract the consumers to participate in the DR program. If the DR program could not be achieved, the first design would be an alternative option for Tidung island.

The second option, the ESS peak load shaving, shows the most massive cost among the others. However, if upgrading cost is considered, and the system in Tidung island almost reaches the capacity limit, the second option might be the best choice considering that the upgrading cost can reach to around $12 million [20] which is almost four times cost of the system.

6. Conclusion

A smart microgrid has been designed for a specific island in Indonesia, the Tidung Island. The design has been initially designed without peak load shaving. The performance of the designed smart microgrid system has been investigated in MATLAB/Simulink for different operating conditions. The simulation results show that the designed microgrid system is stable for all above four operating conditions and maintain the system frequency and voltage and the battery SOC within the recommended national/international limits.

To improve the main grid load profile, peak load shaving capability using ESS and DR have been added to the designed system. It is shown that the system with peak load shaving using ESS with battery capacity of 7.4 MWh smoothens the main grid load pattern much more than the system with DR peak load shaving with 30% consumer participation. However, a CBA is conducted, and the results show that the cost of the system with DR peak load shaving is the lowest among the three options and hence it is concluded that this option would be the best choice for the Tidung Island.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Author A conducted the research with the guidance and help of Author B. All authors had approved the final version of the paper.

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