Optimized configuration of photovoltaic and battery energy storage system (BESS) in an isolated grid: a case study of Eastern Indonesia

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Abstract. Most power systems in the east of Indonesia require only small capacities which are supplied by diesel generators, especially in the area of small islands which are suitable for isolated grid. On the other hand, Indonesia has a high potential for solar energy which can be employed to supplement the power generation as well as to reduce the cost of energy (COE). However, the utilization of solar energy through the photovoltaic (PV) system might cause stability problems. The battery energy storage system (BESS) has been recognized for its capability to overcome stability issues. Still, the adoption of a hybrid PV system and BESS requires considerable capital investment, which may cause the COE to increase. This study identifies the optimal hybrid configuration of the diesel power plant, PV system, and BESS to maximize economic profit when compared to diesel power plants of an isolated grid in Indonesia. COE is used as an economic parameter to determine the most optimal capacities of the PV system and BESS. The simulation results show that the proposed hybrid configuration has a lower COE compared to diesel power plants, which are below 20.81 cents USD[1].

1. Introduction

Population demographics of eastern Indonesia are spread due to the geographical condition which consists of large and small islands [2]. This condition causes the power system in eastern Indonesia to be divided according to the population distribution. Since the population density of these regions is not high, most power systems especially in small islands are suitable for isolated grids. Moreover, Indonesia has a high potential for solar energy, around 536 GW, so the development of the photovoltaic (PV) system can be enlarged in these isolated grids.

However, the major drawback of renewable energy sources (RES) is the unpredictable and intermittent power generation [3]. This issue can be overcome by integrating a hybrid renewable energy system (HRES) including a battery energy storage system (BESS) [4]-[4]. Since the use of BESS usually increases the overall cost, the feasible energy management strategy and appropriate sizing components are needed to produce the optimal design of HRES. Moreover, the proper energy management system can improve voltage stability, ensure continuity of power supply, and protect components from being overloaded [5].

Load following (LF) and cycle charging (CC) are dispatch strategies used to control generator and BESS on HOMER Pro software. Under the LF strategy, when a generator is needed, it only produces enough power to meet the demand without charging the battery. The battery is charged only by the
excess power from the RES. Under the CC strategy, when the generator is switched on, it runs at maximum rated capacity to supply the net load and charge the battery with excess energy [6].

There have been many previous papers discussing HOMER and determine the optimal HRESs design using LF and CC strategies. Sharma and Mishra [7] used CC to analyzed a hybrid optimization model that consists of a grid, PV, biomass generator, and batteries for a smart grid distributed generator. Sandeep and Vakula [8] also used CC to perform an optimal combination of a standalone hybrid power system. Other studies used both strategies to find the optimal HRES design. K.das and Zaman [9] investigated the performance of PV/Diesel/Battery system for a standalone hybrid application in a remote community and found that combine dispatch (CD) strategy has lower COE compared to LF and CC strategies, but for the operational emission for LF strategy is lower than other two strategies.

Based on previous studies, the optimal dispatch strategy depends on the system. However, those strategies have their drawbacks. The objective of this paper is to determine the optimal configuration of HRES using both control strategies on an isolated grid in Indonesia.

This paper consists of four chapters as follows. Chapter one presents the introduction, which explains the background of the study based on previous studies that have been done. Chapter two presents the methodology, which describes the simulation using HOMER Pro software with additional information on the load profile, system components, meteorological data, and control strategy using LF and CC. Chapter three presents the result obtained, including optimization, sensitivity, and economic analysis. And finally, the conclusion is given in chapter four.

2. Methodology
2.1. Site profile and load demand data
The isolated grid selected as a case study in this research located on a small island in eastern Indonesia. Error! Reference source not found. shows the daily average of load demand with a 10% random variability of time-step and day-to-day to provide better reliability. The total energy demand of 138,049 kWh/day, a daily average of 5,752 kW, and a peak load of 12,073 kW are obtained.

![Figure 1. Daily average load demand in the area studied](image)

![Figure 2. Annual solar radiation in the area studied](image)

2.2. Solar energy source
Solar energy data is used to calculate the PV output power. HOMER software uses the monthly average global horizontal radiation as input parameters. The solar radiation and clearance index data for the selected site are represented in Figure 2. The annual average of solar radiation is 6.38 kWh/m²/day, with maximum solar radiation (7.53 kWh/m²/day) is obtained in October, and minimum solar radiation (5.5 kWh/m²/day) is obtained in June. These data indicate that the PV systems have good prospects for implementation because the amount of solar radiation received is relatively high.

2.3. Hybrid system modelling
The proposed hybrid system in this study consist of four components, i.e. diesel generator, PV system, interlink bidirectional AC/DC converter, and batteries. A schematic diagram of the proposed hybrid system is illustrated in Figure 3. Table 1 shows the techno-economic input parameters for all system components.
To ensure balanced power in the system, this following equation should be satisfied at any simulation time step,

\[ P_{\text{load}} = P_{\text{gen}} + P_{\text{PV}} + P_{\text{bat}} \]  

(1)

| Component    | Capital cost ($) | Replacement cost ($) | O&M cost ($) | Lifetime  |
|--------------|------------------|----------------------|--------------|-----------|
| Generator    | 0                | 0                    | 0.014/op.hours | 20000 hours |
| Converter    | 550              | 500                  | 0            | 15 years  |
| PV           | 760              | 152                  | 10/years     | 25 years  |
| Battery      | 450              | 200                  | 6/years      | 15 years  |

### 2.4. Control strategy

LF and CC are dispatch strategies to control the hybrid PV/diesel/batteries system. In this study, these two control strategies are compared to find the most cost-effective combination of PV/diesel/battery. Figure 4 shows the LF and CC dispatch strategy of diesel/PV/battery system.
2.4.1. Load following. This control strategy can be divided into three cases, as follows:

- When the PV output is equal to the load, PV output is used to meet the load demand without charging the batteries. In this case, the generator stays off and no excess power is generated.
- When the PV output is higher than the load, the excess power is charged by the battery. If the battery is fully charged, the excess power will be damped, and the generator still does not work.
- When the PV output is lower than the load, there will be two possible subcases according to the battery SOC. If the SOC reaches its minimum value, the generator will produce enough power to satisfy the netload. And if the minimum generator loading power output is higher than the net load, the excess power charges the battery. Meanwhile, if the battery SOC is higher than its minimum value, there will be a cost of decision that should be chosen between discharging the battery and turning on the generator. The lowest one is used to supply the load.

2.4.2. Cycle charging

The operating system of this strategy is similar to the LF strategy. The difference is, when the generator is switched on, it will run at its maximum capacity to serve the net load and charge the battery with excess power.

3. Simulation and result

3.1. Simulation result

The results show the optimal combination of diesel/PV/battery is under CC strategy, consist of PV 14,572 kW, diesel 14,562 kW, battery 7,964 kW, and converter 7,282 kW. NPC and COE obtained are $126,349,125.32 and $ 0.135 respectively, lower than LF strategy which has $130,404,453.88 of NPC and $0.139 for COE. Moreover, combining diesel/PV/battery resulting in lower COE compared to diesel power plant which has $0.175 of COE.

The renewable fraction of CC strategy is lower than LF which were 34.5% and 39.7%, respectively. This is because the generator under the LF strategy only produces enough power to satisfy the load without charging the battery, while under CC strategy, whenever the generator has to operate, it will operate at its maximum capacity with surplus power going to charge the battery. Thus, diesel consumption under CC strategy is higher. The total amount of generator operating hours in both control strategies is around 8000 – 9000 hours per year.

Implementing an HRES is capable of reducing emissions. Greater diesel consumption resulting in greater greenhouse emissions. CC strategy has higher emission than LF strategy which was 20,896,171 and 19,985,587 kg/year, respectively. Table 2 shows the optimization result of both control strategies.

| Item                              | Unit   | Load Following | Cycle Charging |
|-----------------------------------|--------|----------------|----------------|
| Diesel generator                  | kW     | 14,562         | 14,562         |
| PV                                | kW     | 16,492         | 14,572         |
| Battery                           | kW     | 7,299          | 7,282          |
| Converter                         | kW     |                |                |
| NPC                               | $      | 130,404,453.88 | 126,349,125.32 |
| COE                               | $/kWh  | 0.139          | 0.135          |
| Generator diesel production       | kWh/year | 30,391,521     | 32,981,400    |
| PV production                     | kWh/year | 31,210,585     | 27,576,523    |
| Total production                  | kWh/year | 61,602,106     | 60,557,923    |
| Renewable fraction                | %      | 39.7           | 34.5           |
| Fuel consumption                  | L/year | 7,589,475      | 7,935,267     |
| Batteries throughput              | kWh/year/battery | 2,978,502     | 3,203,618     |
| Batteries nominal capacity        | kWh    | 10,912         | 8,133          |
| Batteries autonomy                | Hour   | 1.33           | 0.99           |
| Excess electricity                | %      | 9,872,056      | 8,686,894     |
3.1.1. Economic analysis. In the LF strategy, the batteries are only charged by solar PV, and as a result, the system becomes more expensive to accommodate the larger size of PV and batteries. Thus, the most cost-effective combination of diesel/PV/battery obtained under CC strategy. Table 3 shows the cost summary of both control strategies. CC strategy has a lower capital cost than the LF strategy which was $18,663,209.71 and $21,356,828.53 respectively, this is because the LF strategy has a larger size of renewable components.

Replacement costs of LF and CC strategies were $5,351,119.28 and $3,395,194.73. CC has a smaller replacement cost than LF because, under CC strategy, the system relies more on generator compared to PV and battery. So that the battery does not require a lot of cost of replacement. While under the LF strategy, the system uses more PV and battery. Moreover, battery accounted for the largest replacement cost in the LF strategy, around 57.23% of the total cost of replacement.

The fuel cost of the LF strategy was $88,711,291.01, lower than the CC strategy, because of the relatively low fuel consumption in the LF strategy. Combining diesel/PV/battery resulting inexpensive O&M cost compared with the diesel generator, which contributed most of the total O&M cost. Meanwhile, the salvage cost of the LF and CC strategies was estimated to be $996,217.37 and $878,406.24 respectively. These costs are obtained from the remaining life of each system component.

| Cost Summary      | Load Following       | Cycle Charging       |
|-------------------|----------------------|----------------------|
| Capital Cost      | $18,663,209.71       | $21,356,828.53       |
| O&M Cost          | $15,981,432.43       | $12,413,293.55       |
| Replacement Cost  | $5,351,119.28        | $3,395,194.73        |
| Fuel Cost         | $88,711,291.01       | $92,753,156.79       |
| Salvage Cost      | $996,217.37          | $878,406.24          |

3.2. Sensitivity analysis
A sensitivity analysis was conducted to investigate the effect of parameters on system performance. The parameters used for sensitivity analysis were battery minimum SOC and diesel fuel price.

3.2.1. Battery minimum SOC. Battery minimum SOC is the minimum threshold for battery SOC to prevent undercharging [10]. $SOC_{min}$ variations used in this study as follows 15%, 20%, 25%, 30%, 35%, and 40%. Figure 5 shows that the increase of $SOC_{min}$ would also increase the $CO_2$ emissions, from 19,490,186 kg/year to 20,371,734 kg/year and the NPC, from $130,333,423 to $131,130,865.

This result indicated the increase of $SOC_{min}$ would increase the system’s dependence on the diesel generator because the battery itself could not be charged effectively. When the system’s dependence on diesel generator was increased, the higher amount of pollution gas was emitted.
3.2.2. Diesel fuel price. Diesel fuel prices will continue to fluctuate over time. This fluctuation encourages the use of RES which has stability towards electricity costs. Diesel fuel prices in eastern Indonesia are currently around $0.63/L with variability over time. To investigated the effect of variations in diesel fuel prices on system performance, a sensitivity analysis was carried out by varying diesel prices of $0.63/L, $0.65/L, $0.67/L, and $0.69/L. Figure 6 shows the increase of diesel fuel price, would decrease the \( CO_2 \) emissions, from 20,896,171 kg/year to 20,585,975 kg/year, while the NPC increased from 126,349,125.32 to 136,197,237.13. It is obvious that the higher diesel fuel price resulting in the higher NPC system. While the use of generator diesel becomes less competitive, so the lower amount of pollution gas was emitted.

4. Conclusion
The optimization results show that the proposed hybrid configuration has a lower COE compared to diesel power plants, which are below 20.81 cents USD. The most cost-effective combination of diesel/PV/battery consist of PV 14,572 kW, diesel 14,562 kW, battery 7,964 kW, and converter 7,282 kW with CC strategy was the optimal solution of this case study by having NPC of $126,349,125.32 and COE of $0.135. The LF control strategy is more suitable for the system with a lot of RESs because the higher RES penetration was obtained under the LF strategy (39.7%), while the CC strategy was 34.5%. Moreover, sensitivity analysis showed the importance of some parameters on system performance such as battery minimum SOC and diesel fuel price.

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