Optimization and comparative analysis for a stand-alone hybrid model of PV, wind turbine, and natural gas generator system in remote area – A case study in Belu

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Abstract. This paper proposes a hybrid model of photovoltaic (PV) and wind power generation based on the off-grid system for the rural area. The off-grid system is considered more suitable to be applied in the remote area since it has a lack of access to the closest grid network. Belu (9°10.5’N and 124°59.4’E), Indonesia, is chosen particularly as the model due to its high potential resources of renewable energy. The data on wind and solar resources are obtained from Meteonorm. The system schematic consists of the wind turbine, photovoltaic (PV), battery, converter and electrical load. A small-size natural gas generator is used as the back-up. The data is processed by using HOMER Optimizer based on the derivative-free algorithm. The total Net Present Cost (NPC) and the Levelized Cost of Energy (LCOE) for the optimized system configuration are $95,828 and $0.106, respectively. The performance of the system is represented by the percentage value of the excess electricity and unmet electric load which are 13% and 0.39%, respectively. The carbon dioxide produced is only 10,070 kg/year. In general, the optimized system is much better compared to the generator-only system based on the economical, electrical, and environmental aspects.

1. Introduction
The electrification ratio is remaining as a concern for remote areas of eastern Indonesia. Most of the household in those areas are living away even from the closest grid. Taking the instance for the area of Nusa Tenggara Timur (NTT) province in Indonesia, the electrification ratio of NTT is still lying on 86.36% (February 2020) [1]. However, the Indonesia government represented by the State Electricity Enterprise, in this case, targets the electrification ratio in Indonesia, especially in NTT, to reach 100%. Hence, in this paper, Belu is chosen as the case model since it has a high potential for renewable energy resource. An off-grid system is better since most of the location is far away from the grid.

A similar study in this field has also been performed by other literature. Hassan et al. (2016) [2], for instance, proposed the optimization analysis of photovoltaic (PV), wind turbine, and diesel generator hybrid system in Budjah, a small remote village in Muqdadiyah district, Iraq based on the off-grid system. However, the most optimum combination of the system to be applied on that rural area was the hybrid of PV and diesel generator, without wind turbine, due to the lack of wind resources available in that area. Whereas, the same hybrid combination has also been presented by Rana Th Abd Al-Rubaye et al. [3] in Diwaniyah, Iraq. The system configuration used PV, wind turbine, battery, and gasoline-type generator. The result showed that the most optimized configuration did not include the generator since it consumed the lowest cost but the highest energy production.
Srivastava and Giri [4] conducted the combination system of the small wind turbine, PV, battery, and a diesel generator as the back-up component in Measurement & Instrument Laboratory at the Electrical Department of Madan Mohan Malaviya University of Technology (MMMUT), Gorakhpur, India. It suggested that all above-mentioned components can be included to generate the system with a lower cost of electricity and net present cost. Their proposed system is suitable enough to be implemented in the country like India, which deficit in electricity.

Last but not least, Yuan et al. [5] offered a unique system by integrating the PV, a wood-syngas combined heat and power (CHP) generator and back-up batteries in a mountainous area at Hubei province, China. As a result, the system was configured based on the Cycle Charging (CC) strategy by involving all those components to possess the lowest Cost of Energy (COE) and Net Present Cost (NPC) for Stand-Alone Power System (SAPS).

By referring to the previous studies, this paper studies the system configuration model comprising PV, wind turbine, and converter. However, since PV and wind turbine cannot fulfil the load on 24 hours basis [6], the operation of a backup generator and battery is required to anticipate the intermittency and variability of these renewable energy resources [7]. The small-size generator used in this model is gas-fueled type generator, which is known to have a lower heating value, Carbon and Sulphur content [8]. Therefore, the optimization of the system configuration also accounts for the amount of emission produced by the system. A software program, Hybrid Optimization Model for Electric Renewable (HOMER), will be employed to perform the system component’s sizing and economic optimization based on the derivative-free algorithm [9]. The objective of the optimization is to determine the most optimized off-grid system configuration by evaluating the Levelized Cost of Energy (LCOE), Net Present Cost (NPC), electrical parameters, and emissions compared to the generator-only system.

The remaining of this paper is as follows: Section 2 describes the data and the methodology used in this paper, including the system configurations, the wind and solar resources, and HOMER optimization. Section 3 covers the simulation results as well as the evaluation of the performance criteria. Lastly, the conclusion is provided in Section 4.

2. Resources & methodology
A hybrid system is preferred since it is more robust compared to the single system of the renewable source generation system. The selected location is in Belu, Indonesia, which is located at 9°10.5’N and 124°59.4’E. The schematic of the system configuration is provided in Figure 1.

![Figure 1. Schematic model.](image)

2.1. Load and energy resources
Load information in Belu is obtained from [10], as presented in Table 1. In the modelling and simulation, this load profile is randomized by 10% of day-to-day variation as well as 20% of the timestep.

| Metric (Unit) | Average (kWh/day) | Average (kW) | Peak (kW) | Load Factor |
|---------------|-------------------|--------------|-----------|-------------|
| Value         | 139               | 5.79         | 14        | 0.41        |
The annual average of the wind speed available is 2.17 m/s, which is measured at the anemometer height of 20 m [11]. The wind speed profile data is obtained from Meteonorm [12]. Table 2 provides the monthly average wind speed data within one year and Figure 2 shows the probability of the hourly wind resource in Belu.

![Figure 2. Wind speed probability in Belu.](image)

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Wind Speed (m/s) | 1.60 | 1.61 | 1.70 | 2.00 | 2.19 | 2.50 | 2.69 | 2.70 | 2.60 | 2.40 | 2.20 | 1.79 |

![Figure 3. Daily global radiation in Belu.](image)

The solar resource radiation used in this study is the Global Horizontal Irradiance (GHI), which is the total amount of shortwave terrestrial irradiance received by a surface horizontal to the ground [13]. Clearness index is a measure of the clearness of the atmosphere [14]. The annual average of the solar resource in Belu is 5.34 kWh/m²/day. Meanwhile, the annual average of the temperature is 27.10 °C. The solar resource and temperature data are collected respectively during the year of 1991-2010 and 2000-2009 from Meteonorm [12]. Table 3 and Figure 3 shows the daily global radiation in Belu.

![Figure 3. Daily global radiation in Belu.](image)

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Clearness Index | 0.44 | 0.45 | 0.47 | 0.57 | 0.57 | 0.59 | 0.60 | 0.60 | 0.59 | 0.58 | 0.58 | 0.48 |
| Daily Radiation (kWh/m²/day) | 4.84 | 4.88 | 4.95 | 5.48 | 4.92 | 4.84 | 5.03 | 5.50 | 5.95 | 6.22 | 6.25 | 5.22 |
| Daily Temperature (°C) | 27.67 | 27.32 | 27.31 | 27.15 | 27.04 | 25.73 | 25.70 | 25.92 | 26.66 | 28.37 | 28.31 | 28.06 |

2.2. Determination of optimized system configuration

HOMER performs multiple optimizations under a range of input assumptions to gauge the effects of uncertainty or changes in the model inputs [15]. Optimization determines the optimal value of the variables over which system designer has control, such as the mix of components that make up the system and the size or quantity of each [16]. The flowchart of the process can be seen in figure 4.

The optimization is started by checking the schematic model firstly. Then, there will be two options of the optimization, either it will be simulated with and without the generator or it will be including the generator in all the simulations. After that, the HOMER will determine the combination and size of the components. Then, HOMER will calculate the total cost (NPC) and the performance of each component. Afterwards, the simulation will consider these parameters, whether the system exceeds the annual capacity shortage, fraction limit, load in the current step, annual peak load limit, and percentage of solar and wind power that have been set previously.

If these parameters exceed the limit value, it will go back again to re-determine the combination and/or size of each component. Otherwise, the system will check whether the system satisfies the system design and NPC precision. If those parameters are satisfied, then the result will be displayed. If not, the system will check whether the system has reached the maximum number of simulation or not. If yes, then HOMER will display the result. If not, the system will re-determine the combination and/or size of the components.
Figure 4. Flowchart of the HOMER optimizer simulation.

3. Simulation results
The schematic of the model consists of the wind turbine, photovoltaic (PV), battery, converter, natural gas generator and electrical load. The controller used on this project is Load Following (LF), that is a strategy that allows the generator to produce the energy power to meet the demand when a generator is needed. This dispatch strategy tends to be optimal in a system with a lot of renewable power that sometimes exceed the load [17]. The price that we input for the natural gas is 0.212 USD [18]. The lifetime of the project is 25 years. The input capacity, lifetime, and cost of each device are shown in Table 4.

| Component   | Capacity            | Capacity Cost ($/kW) | Capital (kW) | Replacement (kW) | O&M / Year ($/kW) | Lifetime   |
|-------------|---------------------|----------------------|--------------|------------------|------------------|------------|
| PV          | to be optimized     | 400                   | 100          | 10               | 25               | 25 years   |
| Wind Turbine| 3 kW                | 1,719                 | 100          | 350              | 180              | 20 years   |
| Converter   | to be optimized     | 260                   | 260          | 7.5              | 20               | 15 years   |
| Generator   | to be optimized     | 1,100                 | 1,100        | 0.018            | 40,000           | 40,000 hours |
| Li-Ion Battery| 1 kWh              | 260                   | 260          | 8.5              | 10               | 10 years   |

The capital cost of the primary component of 3 kW wind turbine is $1,100.00 [27], which is only 64% of the investment cost. The remaining 35% of the total cost is for the Balance of System (BOS), which includes the grid connection cost (transformers and substations), foundation cost (construction, installation, and the other related infrastructure), and planning and miscellaneous cost (licensing, consultancy and the others) [21]. For this reason, the total capital cost for the wind turbine after the calculation by including the BOS cost is $1,719 as shown in Table 4.

The simulation result shows that the optimized system configuration requires a generator and batteries as the back-up. Furthermore, we also simulate a system by including the generator only...
without the renewable energy source and battery as the comparison for the optimized system configuration. The complete result summary is provided in Table 5.

Table 5. The result summary for the optimized system and generator-only system.

| Component size                  | Optimized system | Generator-only |
|----------------------------------|------------------|----------------|
| PV (kWp)                         | 34.2             | 0              |
| Wind turbine (kWp)               | 3                | 0              |
| Battery (kWh)                    | 69               | 0              |
| Generator (kW)                   | 6                | 15             |
| NPC (USD)                        | 95,828           | 150,374        |
| LCOE (USD/kWh)                   | 0.106            | 0.17           |
| Energy production (kWh/year)     |                   |                |
| PV system                        | 47,626           | 76.6%          | 0              | 0              |
| Wind turbine                     | 543              | 0.87%          | 0              | 0              |
| Generator                        | 14,020           | 22.5%          | 59,783         | 100%           |
| Excess electricity (kWh/year)    | 8,114            | 13%            | 48             | 0.095%         |
| Unmet electrical load (kWh/year) | 197              | 0.39%          | 48             | 0              |
| Emission (kg/year)               |                   |                |
| Carbon Dioxide                   | 10,070           | 41,118         |
| Carbon Monoxide                  | 33.5             | 137            |
| Nitrogen Oxides                  | 70.3             | 287            |
| Particulate matter               | 0.944            | 3.85           |

The total Net Present Cost (NPC) for the optimized system configuration is 95,828 USD while the generator-only system costs 1.6 times more expensive compared to the optimized system by spending 150,374 USD. The Levelized Cost of Energy (LCOE) generated by the generator-only system is 0.166 USD/kWh and it is also 1.6 times more expensive compared to the optimized system configuration which spends only 0.106 USD/kWh. For the optimized system, the load demand is mostly supplied by the PV (76.6%) since the solar resource in Belu is more abundant compared to the wind resource (0.87%).

The performance of the optimized system is evaluated by comparing it to the generator-only system. The excess electricity is 13% and 0.39% for the optimized system and generator-only system, respectively. Whereas, the unmet load is 0.39% for the optimized system and zero for the generator-only system. The unmet load of the optimized system is still below 1% as required by the regulation. On the other hand, the optimized system produces a much lower emission compared to the generator-only system, resulting in a more environmentally-friendly system.

4. Conclusion
This paper has shown the investigation on a hybrid system consisting of a PV system, wind turbine, natural gas generator, and battery which can be used in Belu, one of a remote area in Indonesia. The system is simulated by using HOMER to account for the technical and economic aspects. The result shows that the Net Present Cost (NPC) and the Levelized Cost of Energy (LCOE) are 95,828 USD and 0.106 USD/kWh, respectively, which can compete for the values of the generator-only system. Hence, this hybrid configuration can be implemented as one alternative to solve the electrification issue in the remote area as well as to supplement the government effort to achieve the emission reduction target. This work can be extended in the future such as by applying a control algorithm that will maximize the renewable energy usage with lower capacity resources as well as with optimized battery size.

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