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RESEARCH ARTICLE

A Design of Economically Feasible Hybrid Energy System with Renewable Energy Ratio Priority

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Abstract

The reduction of fossil fuels which produce CO_2 emission that damage the environment, can be done by implementing renewable energy-based power generations, such as solar and wind. This research designs a hybrid energy system by optimizing the use of existing diesel generators through the integration of renewable energy sources, such as solar photovoltaic and micro wind turbine, and is equipped with an energy storage system. This research uses HOMER Pro software to determine the optimal capacity of hybrid system components, and to calculate the Cost of Energy (CoE). Furthermore, the hybrid system configuration is analyzed by applying several objectives. The objectives of the hybrid system design are to prioritize a maximum renewable energy penetration ratio within permitted annual capacity shortage, and with the CoE lower than the existing CoE. The research results show that the proposed hybrid energy system can provide a renewable energy penetration ratio of 57.1% with CoE of IDR 3,510/kWh.

Keywords: power systems, hybrid systems, cost of energy, renewable energy penetration ratio

1. Introduction

Energy is one of the contributing factors of social and economic development of a region, especially isolated areas in developing countries. The availability of energy, especially electricity, can create economic growth, eradicate poverty, create jobs, and improve the standard of living in rural areas [1]. However, most of these isolated areas are not connected to electricity grid, either because of geographical conditions that do not support it, or because of the lack of availability of public utilities. The unavailability of this electricity grid will hamper the development of public facilities that depend on electricity, for example telecommunications facilities, health facilities, and telecommunications facilities [2]. One of the areas with a low electrification rate in Indonesia is the Mentawai Islands in West Sumatra Province, with a percentage of 21.7% in 2016. Compared to the average of West Sumatra province which has reached 73.5%, this percentage is still very low [3]. Therefore, efforts are needed to increase electrification in the Mentawai Islands area, especially in Sikakap District.

Currently, the solution to provide electricity in the area is to use diesel generators. However, the use of diesel generators can cause various problems, such as the emergence of dependence on fossil fuels that are vulnerable to price changes, and the need for transportation to provide fossil fuels, so that it does not guarantee the readiness of diesel generators to generate electricity [4]. On the other hand, the operation of diesel generators at a low electricity load factor, i.e. less than 40% of the generation capacity of diesel generators, is considered inefficient and will reduce the service life of the diesel generators and increase repair costs [5]. In addition, the limited amount of fossil fuels and greenhouse gas emissions from conventional energy sources such as diesel generators are also a problem. The government is trying to reduce greenhouse gas emissions by increasing the penetration ratio of renewable energy in these systems [6], [7].

To overcome these problems, the use of renewable energy-based generators is one solution that can be considered. Generally, the renewable energy used are in the form of Micro Wind Turbine (MWT) system and Solar Photovoltaic (PV) system. However, one disadvantage of using renewable energy-based generators is their intermittent nature, due to weather and climate factors [4]. Therefore, electrical energy storage devices such as Battery Energy Storage Systems (BESS) can be used to improve the reliability of the electrical system that uses renewable energy-based generators [8]. However, the implementation of a hybrid energy system with MWT system, Solar PV system, and BESS requires a significant investment cost. The renewable energy penetration ratio is directly proportional to the addition of energy costs. Therefore, a mechanism is needed to determine the optimal penetration ratio with the objective of obtaining high renewable energy penetration with the condition of cheaper energy costs and high energy availability. Many studies have explored the use of renewable energy, especially Solar PV system with BESS combined with diesel generators [4], [5], [8], [9], or those using MWT system [10], [11].

This research will study the potential use of a combined or hybrid energy system by integrating diesel generators, Solar PV system, MWT system, and BESS. The main technical contribution of this research is on the selection method for the optimal configuration of the hybrid system in the case of some limitations exist. For instance, the hybrid system configuration shall have a maximum possible portion of renewable energy, meet the maximum allowable capacity shortage, and the resulted cost of energy shall be lower than the exising one. This study utilizes HOMER Pro software, which is a software that functions to perform optimal microgrid calculations [9]. Furthermore, the selection of technical configurations that meet the highest penetration ratio, lowest energy costs, and low energy unavailability is selected through cost-benefit analysis.

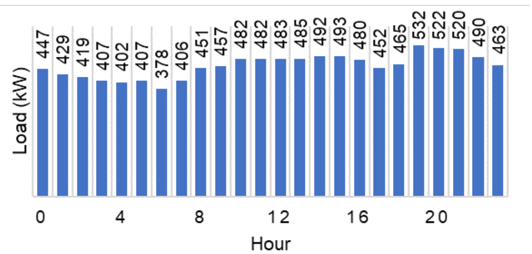
For this, this research attempts to incorporate the extended mechanism to select the hybrid configuration resulting from HOMER software. This research is expected to contribute to the development of a more optimal renewable energy system and reduce human dependence on the use of fossil energy.

This research is structured as follows: Section 2 explains the data used in this research and the method for determining the optimal capacity for the desired purpose, Section 3 presents the results of the research, and the conclusions are given in Section 4.

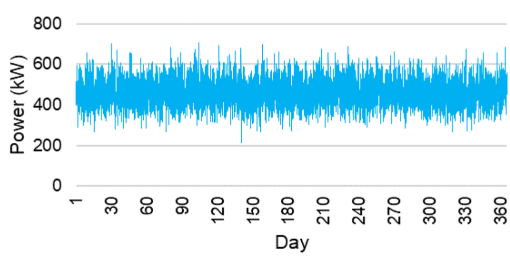
2. Research Methodology

2.1 Existing Generator and Load Profile

This study uses data and conditions in Sikakap, Mentawai Islands Regency, West Sumatra Province. Sikakap is supplied by three diesel generators with installed power capacities of 500 kW and 2 × 250 kW. The existing energy cost is IDR 4,031 per kWh, which is dominantly affected by the fuel cost. Sikakap's peak load reaches 705.7 kW with an average load of 460.16 kW, giving a load factor value of 65%. To provide variations that are close to actual conditions in the field, this study applies a random variability of 5% for day-to-day and 10% for hour-to-hour. Thus, the average daily energy consumption is 11,043 kWh/day. The Sikakap load profile is shown in Figure 1.



(a)



(b)

Figure 1. Sikakap Load Profile, (a) Average daily load profile, (b) Annual load profile

2.2 Solar Radiation Data

The output power of Solar PV system can be influenced by several parameters, including solar radiation, clarity index, and ambient temperature. Solar radiation data in this study were obtained from the Prediction of Worldwide Energy Resources (POWER) database provided by the National Aeronautics and Space Administration (NASA), as shown in Figure 2. Based on this data, the highest solar radiation occurred in April at 5.22 kWh/m^2/day, and the lowest radiation emission in November at 4.55 kWh/m^2/day.

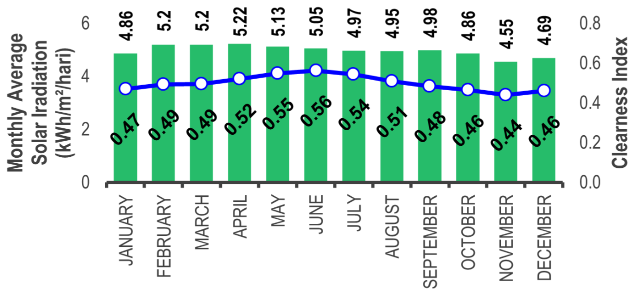


Figure 2. Solar radiation data and average brightness index per month in one year

2.3 Wind Speed Data

The energy produced by wind turbine depends on the wind speed at the height of the turbine, which is obtained from NASA's POWER database. Figure 3(a) shows the average wind speed data at the research location based on anemometer measurements at a height of 10 m above ground level. The highest average wind speed occurred in January (4.12 m/s) and the lowest in May (3.74 m/s). Meanwhile, Figure 3(b) shows the variation in wind speed against the height of the wind turbine. The type of wind turbine proposed in this study is for installation at a height of 6 meters above ground level.

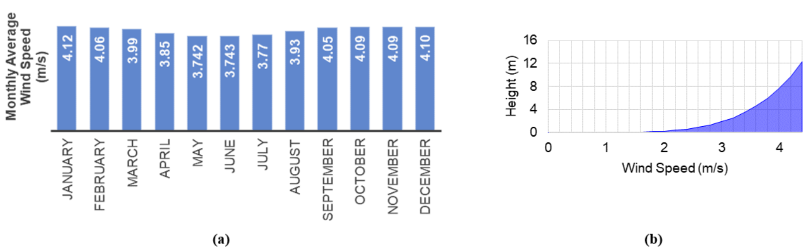


Figure 3. Average wind speed data per month in one year

2.4 Hybrid Energy System Development

The hybrid energy system consists of the existing diesel generators, the solar PV system, the MWT system, and BESS completed with Power Conversion System (PCS), as presented in Figure 4. The development of the system is determined by the algorithm presented in Figure 5. Data collection is conducted to gather inputs required for the optimization process, i.e. load profile, diesel generator configurations, solar radiation profile, wind speed profile, and costs related to each type of generation. The 1st optimization process is then conducted with optimal values determined by the HOMER Pro software. The optimization process produces several configurations, which is denoted as C_k for the k-th configuration. For each configuration, C_k, the hybrid system may consist of mix of diesel generators, MWT system, Solar PV system, or BESS. The results are then sorted out from the highest renewable energy penetration ratio (r). Each of the sorted results are then filtered out by iteration based on several factors to determine a configuration that best suites the objective of this research. The factors of the configuration include an annual energy shortage (S) of less than 3%, and a CoE lower than the existing CoE.

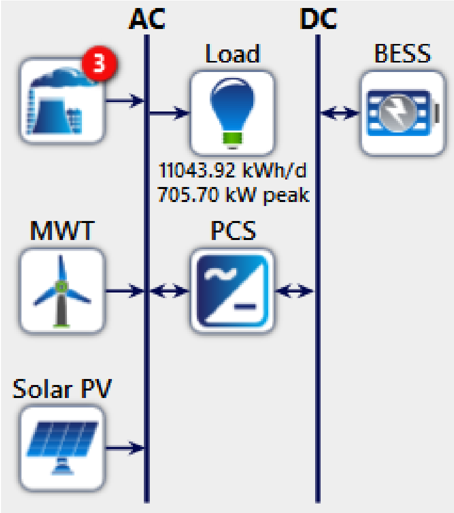


Figure 4. Hybrid energy system configuration

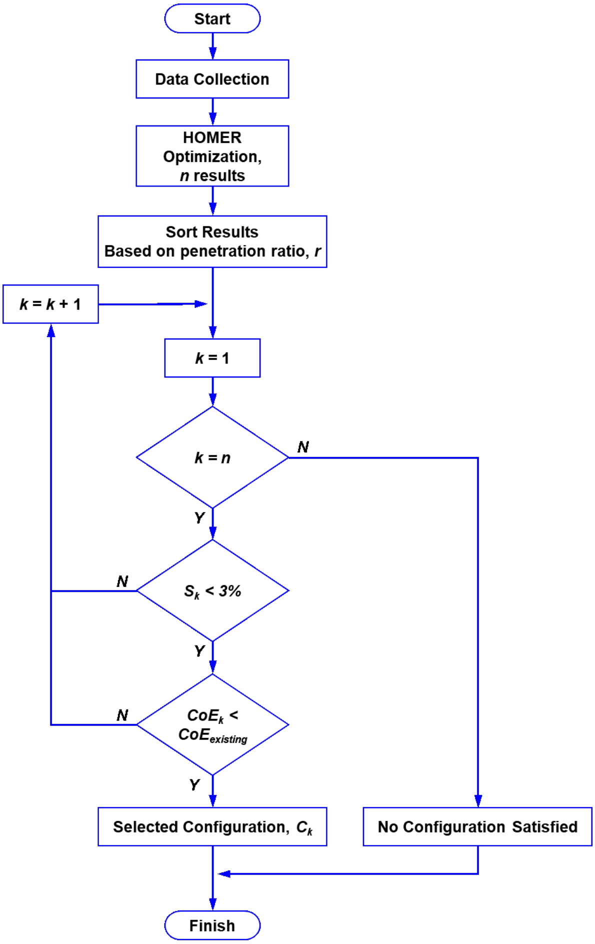


Figure 5. Proposed hybrid energy system development algorithm

3. Results and Discussion

3.1 Characteristics of Existing Generators

The generators' characteristics can be defined based on their fuel efficiency. For this research, such information is assumed as in Figure 6. The assumption is made based on the generators' size and age. Therefore, the generators are required to operate at least at 40% (200 kW) for 500 kW rated generator, and 50% (125 kW) for 250 kW rated generator, to maintain the efficiency greater than 25%. It is worth to note that, the development results is sensitive to this efficiency curve, especially the value of hybrid CoE. This value is obtained through weighted summation of the energy provided by the existing generators and the renewable energy generation system. However, for research purposes, the proposed method is robust and can be implemented in any case with such adjustment in the data.

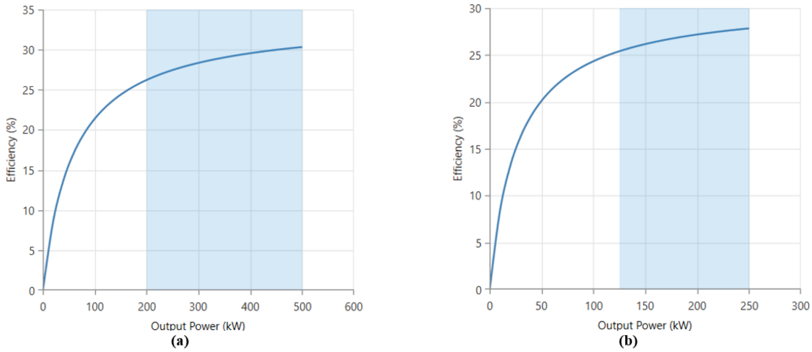


Figure 6. Generators' fuel efficiency curve, (a) 500 kW, (b) 250 kW

3.2 *Cost Data*

The development of the hybrid energy system requires the component's costs, which include the capital expenditure (CAPEX), replacement expenditure (REPEX) and operational expenditure (OPEX). The cost data has considered the material, logistics, and installation cost. The summary of the cost data used in this research is provided in Table 1. The fuel price used in this research is assumed to be IDR 11,000 per liter. Moreover, a fixed cost for the integration of distribution network is also considered, which is estimated at IDR 240,000,000.

Table 1. Data of system components

Component	Unit Capacity	CAPEX (IDR)	REPEX (IDR)	OPEX (IDR)	Lifetime
Generator 1 (500 kW)	250 kW	-	375,000,000	8,000/hour	40,000 hours
Generator 2 (250 kW)	250 kW	-	150,000,000	6,000/hour	40,000 hours
Generator 3 (250 kW)	500 kW	-	150,000,000	6,000/hour	40,000 hours
Solar PV System	1 kWp	5,400,000	30% of CAPEX	120,000/year	20 years
MWT System	10 kWp	48,000,000	50% of CAPEX	1,200,000/year	20 years
PCS	6 kW	60,000,000	50% of CAPEX	1,200,000/year	20 years
BESS	1.2 kWh	7,200,000	100% of CAPEX	120,000/year	5 years

3.3 *Calculation Result*

The first optimization is conducted by using HOMER Pro with a nominal discount rate of 12%, and an inflation rate of 2.5% per year. The project lifetime is expected to be 20 years. Some options of the hybrid system configuration sorted out based on the maximum renewable energy penetration ratio are presented in Table 2.

Table 2. Calculation results of the hybrid energy system development

Configuration Option	Diesel Generator (kW)	Solar PV System (kWp)	MWT System (kWp)	BESS (kWh)	PCS (kW)	Renewable Energy Penetration Ratio (%)	Capacity Shortage (%)	CoE (IDR/kWh)
1	-	11,000	-	9,200	706	100	2.94	6,108
2	-	8,283	2,130	8,010	901	100	3.04	5,515
3	250	5,782	2,930	5,500	433	84.8	2.72	4,644
4	750	3,313	-	4,600	706	68.6	0.1	4,038
5	500	2,761	830	2,300	529	57.1	1.87	3,510
6	1,000	-	-	-	-	0	0	4,031

3.4 Discussion

From the calculation, it can be seen that the configuration which provides 100% renewable energy penetration (IDR 6,108/kWh in Option 1 and IDR 5,515/kWh in Option 2) results in energy cost higher than the existing one (IDR 4,031/kWh). Similarly, the other option that consists of solar PV system, MWT system and BESS can penetrate 84.8% of renewable energy, but the CoE is IDR 4,644/kWh, which is greater the existing CoE. On the other hand, the design that can give the lowest capacity shortage other than the fully operated diesel generator is Option 4, which can reach a renewable energy penetration as high as 68.6%. However, the CoE of this system is still slightly higher than the existing CoE, which is IDR 4,038/kWh.

According to the results, the configuration and capacity mix that best suites the objective of this research is Option 5, with the utilization of 500 kW diesel generators combined with the renewable energy system. The renewable energy sources consist of Solar PV system of 2,761 kW, MWT system of 830 kW, and BESS with a total capacity of 2,300 kWh, and the PCS of 529 kW. This combination of renewable energy sources resulted in 57.1% of renewable energy fraction. Furthermore, the capacity shortage of this configuration is only 1.87%, and the CoE of this configuration is IDR 3,510/kWh, which is cheaper by IDR 521/kWh than the existing CoE of IDR 4,031/kWh. Hence, both the capacity shortage and CoE parameters fulfills the determined criteria.

Option 4 might provide an attractive preference due to its CoE that is close to the existing CoE, such as IDR 4,038/kWh and IDR 4,031/kWh. Moreover, it provides a higher renewable energy penetration than Option 5, as well as a lower annual capacity shortage. In this case, if the 0.17% CoE difference is not an issue among the stakeholders, Option 4 will be a better choice, especially if the developer of the hybrid system can optimize the unit cost of the components during the procurement. But, if that cost difference cannot be contested, then Option 4 is the most optimal design.

The demand-supply curve of the selected hybrid system configuration in various days are presented in Figure 7 - Figure 9. Each figure represents different daily power demand curve and different weather conditions, which provide impacts on the energy production of Solar PV system and MWT system. An example of high power generation occurred on June 24th, mainly due to clear sky conditions. This high power generation also shows an over-supply condition, which enables the BESS to store excess energy to then be discharged at later times when the renewable energy sources are not producing any power. On the other hand, the solar PV production tends to decrease when the sky is cloudy or partially cloudy. The decline tends to better fit in with the load profile for each respective dates. However, the BESS utilization will not be as optimal as the other cases, due to lower excess energy stored. In addition, the power production from MWT is quite low due to smaller capacity of the MWT.

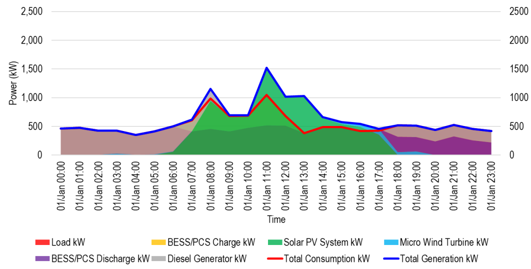


Figure 7. Snapshot of the demand-supply curve on January 1st (Partially Cloudy)

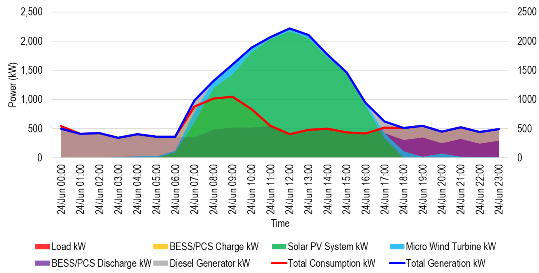


Figure 8. Snapshot of the demand-supply curve on June 24th (Clear Sky)

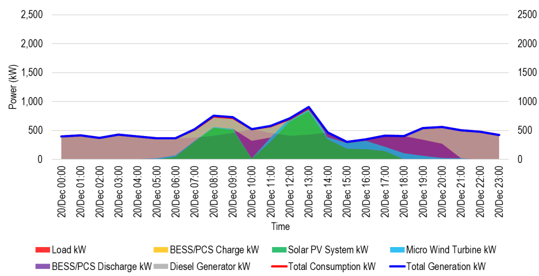


Figure 9. Snapshot of the demand-supply curve on December 20th (Cloudy)

4. Conclusion

This research aims to develop an optimal hybrid energy system that consists of the solar PV system, MWT system, and BESS to supplement the existing diesel generators. The objective of the design is to have the renewable energy penetration as high as possible with the constraint of a lower energy cost. Hence, the proposed hybrid energy system must have a lower CoE than the existing one. Besides, the design is also limited by the maximum allowed capacity shortage, which is 3% annually. For this, this research proposes a method by employing the optimization provided by HOMER Pro software. In addition, a further filtering analysis is applied in the algorithm to obtain the optimized hybrid system configuration.

The result shows that the selected hybrid energy system configuration comprises of 500 kW of diesel generator, 2,761 kWp of solar PV system, 830 kWp of MWT system, and 2,300 kWh of BESS completed with 529 kW of PCS. This configuration results in 57.1% of renewable energy penetration, with an annual capacity shortage of only 1.87%. The CoE of the proposed configuration is IDR 3,510/kWh, which is lower by IDR 521/kWh compared to the existing CoE of IDR 4,031/kWh.

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