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Study of Potential Scalability Development of Palm Oil Mill Effluent-based Gas-fired Power Plant

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ABSTRACT

Indonesia, as the world's largest producer of palm oil, generates a large amount of liquid waste that has the potential to be a renewable energy source. The main problem of liquid waste originated from palm oil industry, apart from its nature, is its potential long-term usability, especially when improvements in biogas-based power generating technologies are put into consideration. Based on these problems, the main purpose of this research is to compare the economical, technical, and environmental scalability between palm oil mill effluent (POME)-based biogas power generation and older, existing diesel-based power generation and analyzing their scalability potential in long term, in aim to increase the utilization of renewable energy portion in Indonesia. This research is conducted by observing an actual palm oil mill facility and its power generation system. Data are analyzed by qualitative and quantitative method by means of computer simulation before being compared with diesel-based power generation system. Based on simulations and comparative analysis, POME-based biogas can be utilized as a fuel source for power generation using gas-fired power generating technology, due to its methane content. With these characteristics, it is possible to analyze the scalability potential of POME-based biogas power plants in the diversification of new and renewable energy sources. Studies on potential development show that biogas power plants are more efficient and have a linear correlation with the volume of liquid waste, and can be adapted in lieu of power generating-related technology advancements. As a result, energy derived from POME can support energy independence and contribute to the growth of clean energy.

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1. INTRODUCTION

Presidential Regulation No. 112 of 2022 serves as a guideline in Indonesia for implementing the energy transition from fossil fuels to renewable energy. Currently, the renewable energy share has only reached 14.11%, with fossil energy still dominating, while the targeted energy share is set at 23% by 2025. The government is striving to accelerate this transition by phasing out coal-fired power plants early and promoting the development of renewable energy [1].

As the world's largest producer of palm oil, Indonesia generates a significant amount of waste that has the potential to be utilized as a renewable energy source. However, liquid waste from palm oil processing remains largely underutilized [2] [3]. In fact, palm oil liquid waste presents an opportunity for environmentally friendly energy while simultaneously addressing environmental and social issues arising from waste disposal. In 2021, approximately 65% of palm oil production resulted in waste [2]. This waste can be processed into biogas, briquettes, or fuel through a co-firing system. The treatment of liquid waste produces methane, which can be used to power biogas-based gas engine power plants.

Biogas-fired Power Generation System (BfPG) technology is similar to natural gas-fueled Gas-fired Power Generation System but is more environmentally friendly as it utilizes palm oil waste [4] [5] [6]. Although the current capacity of palm oil waste power plants does not exceed 1.5 MW per unit, this technology is easy to develop and does not require complex power generation architecture. To increase capacity, a study on the potential waste that can be converted into usable power plants' fuel is necessary. In addition to potential studies, a comparative analysis between palm oil waste-based power generation systems and diesel-fueled systems—considering factors such as cost, waste volume, and fuel procurement—is needed to assess the feasibility of scalability development [7] [8] [9].

The advantages of palm oil biogas power plants include higher energy efficiency, lower fuel costs, faster engine heating times, and lower greenhouse gas emissions compared to diesel power plants [7] [8]. Furthermore, this technology reduces dependence on fossil fuels [9] [10] [11] and minimizes the need for waste reservoirs, thereby improving the productivity of palm oil plantations without requiring new land expansion. Palm oil biogas power plants offer a more sustainable and economical solution, especially for companies with direct access to palm oil waste [8] [12] [13].

With aims to study the possibility of advantages of utilization of POME-based biogas power generation system, and to study its potential prospects, this research paper concerns about the advantages of POME-based biogas produced by the gasification of palm oil mill effluent over diesel-based power generation in terms of economic, technical, and environmental impacts. This research paper also concerns with the simulations' main scenarios to determine the prospects of improvements in POME-based biogas power generation in lieu of power-generation technologies in the future (especially in terms of power plants' efficiency/power factor) and its effects on palm oil mill's thermal load controller (TLC). To fulfill these purposes, this paper applies an integrated approach that optimizes technical, economic, and environmental aspects to enhance the scalability of POME-based biogas power generation system to allow the possibility of having output capacity of 2 MW or greater. Scalability development is based on an analysis of local energy demand fulfillment through software-based simulation-analytical methods while also addressing environmental issues caused by the palm oil industry and reducing dependencies on fossil fuels in power generation system at the same time.

2. METHOD

The methodology used to analyze the scalability potential of a biogas-based power generation system from palm oil mill effluent (POME) is a qualitative-quantitative methodology. The qualitative aspect involves optimizing the power system of a palm oil biogas system with minimal load on the thermal load controller (TLC) and comparing the emission levels of biogas-based power plants with diesel-based power plants. The quantitative aspect lies in the scalability potential of the system, which allows the power output of the biogas-based power generation system to be increased to a larger scale by considering advancements in power generation technology.

The objective of this research is to compare the combination of a biogas-based gas engine power plant using palm oil biogas with other types of power generation combinations, considering economic analysis and benefit analysis in addressing issues related to palm oil mill effluent. To achieve this objective, the research steps are outlined in Figure 1.

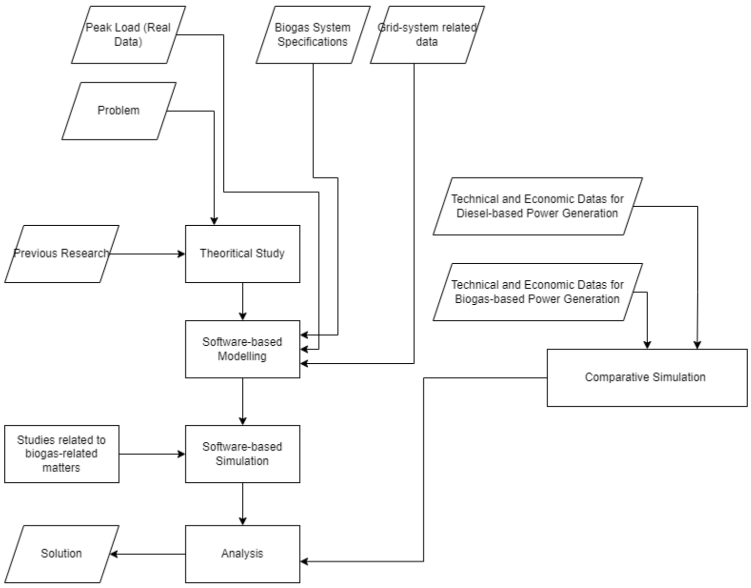


Figure 1. Stages of research for determining scalability aspects of POME-based biogas power generation system

Based on Figure 1, the research steps can be described as follows:

1. Accurate Data Input
   This includes technical data on palm oil mill effluent, cost per kWh of the POME-based power generation system, supporting literature studies such as previous research on palm oil biogas, power plant system design, potential power output, and the environmental impact of diesel power generation as a basis for comparison and analysis.
2. System Modeling
   The modeling will use HOMER simulation software [14] [15] to model the gas engine power plant considering gas engine parameters, generators, grid systems, and daily fuel input data.
3. Simulation of Modeling Results
   After modeling, a comparative simulation will be conducted using HOMER software [16] [17] [18] [19]. The simulation will compare the scalability, economic, and environmental aspects of five scenarios.
   a. The first scenario is a power generation system that relies entirely on biogas.
   b. The second scenario is a combination of biogas and other renewable energy sources (RE).
   c. The third scenario is a combination of biogas, other renewable energy sources, and diesel power plants.
   d. The fourth scenario is a combination of diesel power plants with renewable energy sources.
   e. The final scenario is a power generation system that solely uses diesel power plants.

   From these five scenarios, the solution with the lowest operational cost, minimal emissions, and maximum scalability potential will be selected.
4. System Stability Analysis
   Next, a system stability analysis will be conducted using simulation software to identify potential issues and improve system stability. A review of the system's response to disturbances and load changes will be performed, including an analysis of its impact on the protection system.
5. Economic Analysis
   At this stage, an economic analysis will be conducted, including net production cost (NPC) and cost of energy (COE) to determine the scalability and economic feasibility of the biogas-based system design. This process will be carried out through simulations using HOMER software and data visualization with Microsoft Excel.
6. Comprehensive Pre-scalability Analysis

At this stage, results from economic analysis and system stability analysis will be comprehensively studied with technical and environtmental variables in mind. The result from this step will result in linear correlation datas in two main scenarios as a prepatory step for scalability analysis.

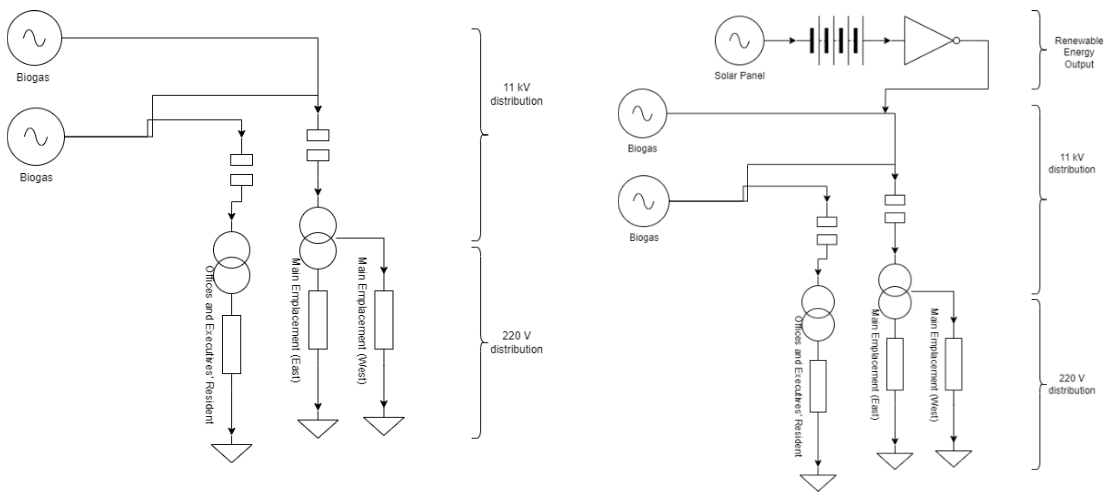
7. Scalability Analysis
   This final step will focus on POME-based biogas power generating system. Based on previous economic, technical, and environmental studies, the potential utilisation of POME for power generating system can be drawn in lieu of power generation technology advancements and impacts on POME-digesting and processing capacity increments. Based on this study, the possible power generating configuration can be determined, either within the palm oil company, outside the corporations' premises, or located in specially-designated locations for POME treatment.

The study compares the technical and economic performance of palm oil biogas-based power generation systems with diesel-based power generation systems. The objective of this research is to optimize the power generation system of the biogas-based power generation system. Through this optimization, it will be determined whether the power plant capacity can be increased and its potential integration with other power generation sources (in this case, solar power plants). The simulation and analysis process assumes no expansion of plantation land (entirely based on existing plantations).

3. RESULTS AND DISCUSSION

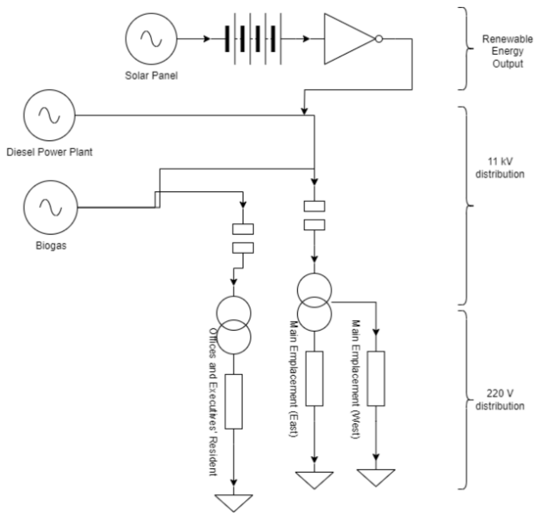
3.1. Real World Technical Study

The electrical system of "X" Corporation consists of two voltage levels: an 11 kV network and a 220 V low-voltage distribution network. This distribution system will be connected to a gas engine power plant using palm oil mill effluent (POME) biogas as fuel. Various modeling scenarios for the power generation and distribution system in the palm oil mill biogas system are presented in Figure 2.

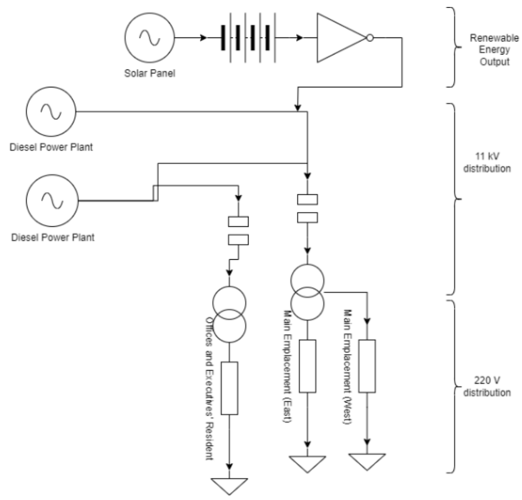


a. Biogas-only scenario

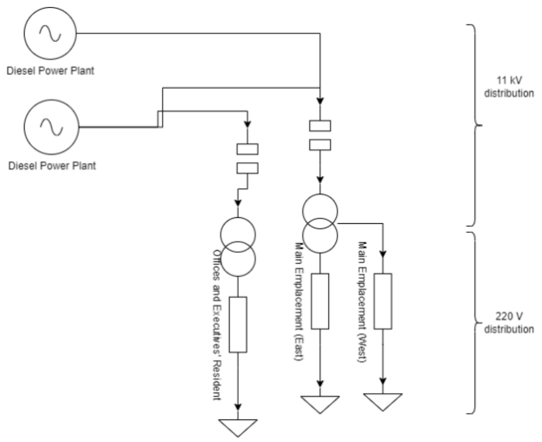
b. Biogas system with solar panel as an auxillary power source



c. Combined system (biogas, diesel, and PV)



d. Combined diesel-PV power generation system



e. Diesel-only system

Figure 2. Comparison of power grid systems between five HOMER simulation scenarios

The grid system consists of three main loads: the executive complex load, the main emplacement load in the western sector, and the main emplacement load in the eastern sector. The executive complex load includes office and residential loads. The western sector emplacement load consists of residential and commercial/public facility loads. Lastly, the eastern sector emplacement load consists of residential and industrial loads (warehousing, telecommunications facilities, and vehicle workshops). As of November 2024, the total load of these three systems is 3 MW.

The power demand is supported by a gas engine power plant as the base load generator, using biogas as fuel. This biogas is obtained from processing palm oil into crude palm oil, where the liquid waste is collected in a wastewater pond located south of the palm oil mill (POM).

The POM processes 90 tons of palm oil per hour. Each processing cycle produces 38 tons of liquid waste, which is then fed into a digester facility behind the POM for biogas production. This facility has dimensions of 320 m × 150 m × 6 m, with two-thirds of the area used for processing and biogas production. The facility can generate 43,200 m³ of biogas per day, requiring 1,800 m³ of biogas to support a 3 MW load with a generator efficiency of 35%.

For the diesel power system, which is still used as a backup power source, there are two engines with a capacity of 1.6 MW each. Field data shows that the diesel power plant consumes an average of 1,140 liters of diesel per day with an engine efficiency of 35%.

The current electrical system utilizes both diesel-based power generation system and biogas-based power generation system, with diesel-based power generation system providing additional power when necessary. The lowest load is 3 MW, while the highest is 5 MW, with diesel-based power generation system supplying up to 2 MW if needed. The operational cost of diesel-based power generation system is IDR 5,300/kWh, while POME biogas is more cost-efficient at only IDR 484/kWh. Industrial diesel fuel in Central Kalimantan costs IDR 15,300 per liter. The use of POME biogas reduces costs and improves efficiency. Five scenarios are tested, as explained in the Methods section. The results from these five scenarios will be used to compare two main scenarios: a biogas-based system and a diesel-based system.

3.2. Technical Study Based on Simulation

The TLC load factor, as an effect of the grid system on the palm oil mill, influences the mill's performance. This is also a key consideration in the scalability analysis of gas-based power generation system expansion using palm oil mill effluent biogas. Therefore, a comparative simulation of five scenarios is conducted, analyzing the TLC load factor at each 3 MW level. The comparison of these five scenarios regarding TLC load based on simulations using HOMER software can be seen in Figure 3.

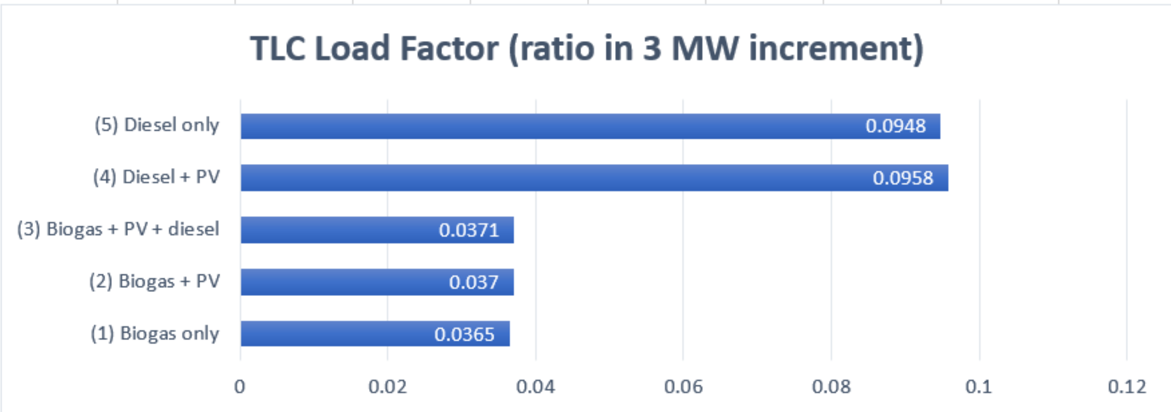


Figure 3. TLC load factor based on five scenarios simulated using HOMER software

Based on Figure 3, it can be concluded that the implementation of a biogas-based power system using palm oil mill effluent can reduce the TLC load, allowing for the expansion of the palm oil mill power system without compromising stability. This is due to the higher efficiency and uptime of the biogas-based power plant compared to diesel generators. As shown in Figure 3, scenarios without biogas generators result in a higher TLC load on the POM compared to systems with active biogas generators. If TLC is exessively overload, it will affect the POM performance stability and safety, and if problem is not quickly been addressed, it will affect the stability of entire power grid.

3.3. Economic and Environmental Effects Studies Based on Simulation

Using HOMER software, the cost of energy (COE) and net production cost (NPC) for each scenario can be determined. Data for each scenario is presented in Figure 4 and Table 1.

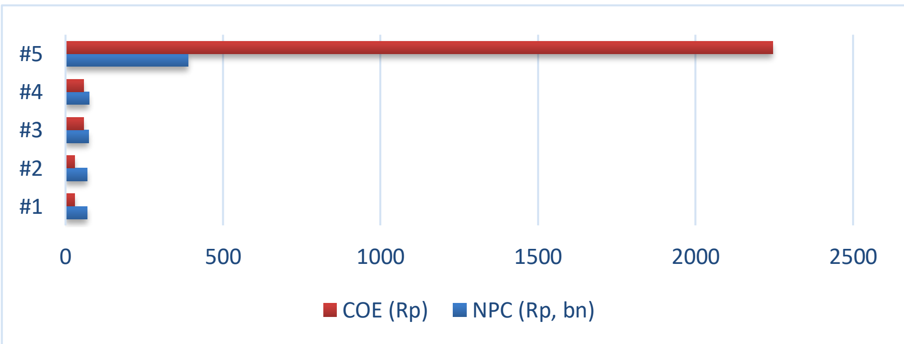


Figure 4. Comparison of NPC and COE scores from each scenario

Table 1. Comparison of NPC and COE scores from each scenario, with its share proportions

Scenario	NPC (IDR, billion)	COE (IDR)	Power Generation Type	Share Proportions
#1	69.3	29.59	Purely biogas-based	Purely biogas-based
#2	69.3	29.59	Biogas and PV	98% biogas-based, 2% photovoltaic
#3	73.4	57.02	Biogas, PV, and diesel	45% biogas-based, 10% photovoltaic; 45% diesel-based
#4	74.4	57.02	Diesel and PV	90% diesel-based, 10% photovoltaic[1]
#5	389	2,245	Diesel only	Diesel only

According to the HOMER simulation, the NPC and COE for the first scenario, where electricity generation relies entirely on biogas, are IDR 69.3 billion and IDR 29.59 per 3 MW, respectively. The project duration is three years, with a payback period of 10 months. These costs are significantly lower compared to a diesel-based power system, where NPC and COE are IDR 389 billion and IDR 2,245 per unit with a net output capacity of 1.6 MW, excluding additional expenditures for diesel engine maintenance and fuel procurement. Therefore, the first scenario using POME biogas offers the best cost efficiency while maintaining scalability. This means that with minimal costs, the potential to increase power generation remains high and affordable compared to the existing diesel-based system. Additionally, biogas-based power plants produce minimal emissions. The environmental impact is illustrated in Figure 5 and Table 2.

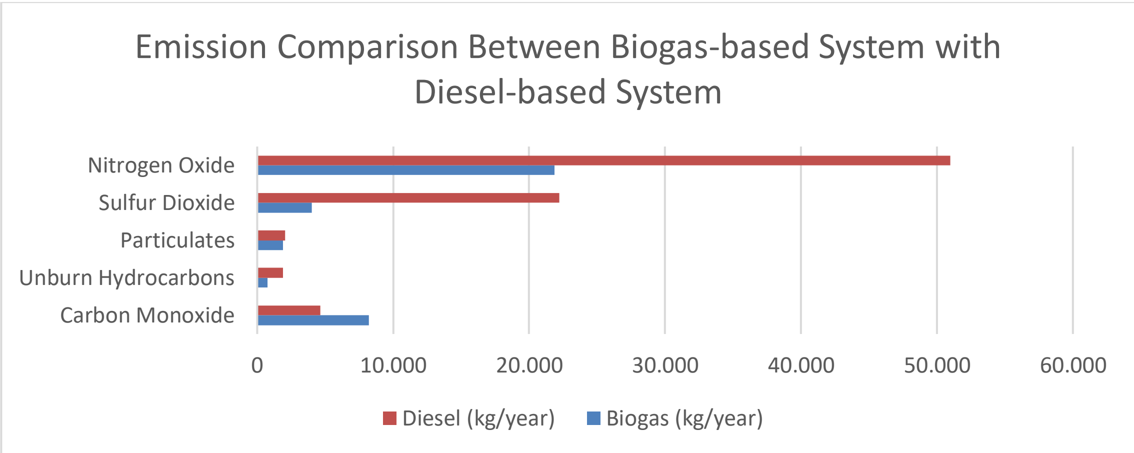


Figure 5. Emission comparison between biogas-based system vis-à-vis diesel-based system

Table 2. Emission comparison between biogas-based system vis-à-vis diesel-based system

Emission substances	Biogas-based system (kg/yr)	Diesel-based system (kg/yr)
Carbon Dioxide	11,877,954	9,009,279
Carbon Monoxide	8,225	4,644
Unburn Hydrocarbon	747	1,880
Particulate	1,885	2,052
Sulfur Dioxide	3,994	22,231
Nitrogen Dioxide	21,862	50,983

Based on Figure 4, the emissions from a palm oil mill biogas power plant are lower than those of a diesel power plant. This is because palm oil biogas power plants produce lower emissions of sulfur dioxide, nitrogen dioxide, and incomplete combustion byproducts compared to diesel generators.

However, gas engine power plants have higher carbon dioxide emissions. Nevertheless, since the power plant is located within a plantation, the CO_2 produced is absorbed by palm trees for photosynthesis, generating

[1] This combined scenario involves switchable power grid system; at daylight, the PV system is more dominant.

oxygen. According to Henson (1999) [20], palm plantations can absorb 161 tons of CO_2 per hectare per year. Given that the biogas-POME power plant emits approximately 11,878 tons of CO_2 annually for a 3 MW output, and “X” Corporation owns 550 km² of plantations, the CO_2 absorption capacity is 8.85 million tons per year. The emission levels at different power outputs for the biogas-based power generation system system are illustrated in Figure 6.

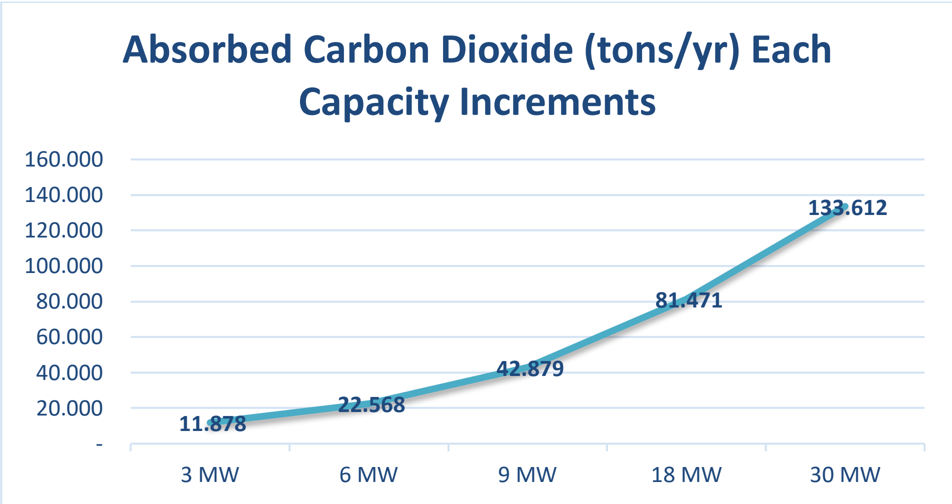


Figure 6. Carbon dioxide emission correlation chart for every power capacity increments

Figure 6 indicates that even if the power plant operates at maximum capacity (up to 30 MW in the simulation), “X” Corporation’s plantation can still absorb the emitted CO_2 for photosynthesis. Additionally, palm trees help mitigate carbon monoxide emissions since trees, including oil palms, are effective carbon sinks. The emission comparison for each power system scenario is provided in Table 2.

Emission factors and efficiency are also influenced by the complexity of the power plant components. Palm oil mill effluent biogas power plants have simpler components. Generally, a gas engine power plant has three main components outside the generator: a turbine, a compressor, and an igniter. Diesel engines, on the other hand, have a more complex structure and require lubricants for optimal and efficient operation. Based on the variables tested using HOMER software, a summary of the potential efficiency of a palm oil mill effluent biogas power plant can be compiled. The efficiency potential of a POME biogas power plant is summarized in Table 3.

Table 3. Summary of advantages from implementation of POME-based biogas power generation system

Comparison Aspects	**Biogas-based System**	**Diesel-based System**
Fuel Availability	Palm oil mill effluent-based, with constant supply from palm oil mill	Diesel-based, subject to transportation cost and market conditions
Cost for Each kWh	Stable, or at least relatively stable	Subject to global oil prices and government regulations.
Sustainability	Available locally and sustainable	Subject to external factors
Investation and Maintenance	Large upfront cost, lower operating cost	Lower upfront cost, but with higher operating and maintenance cost
Effects on TLC	Minimum	High impact on TLC
Environmental Effects	Lower emission	Higher emission, especially on greenhouse gases.

3.4. Economic Scalability Comparison Between Two Main Scenarios

Apart from cost, technical, and fuel availability aspects, the TLC load factor affects power system scalability. This is because adjustments to TLC may be necessary depending on specific load requirements, thus affecting costs of O&M. Other scalability factors include system installation and modifications to the existing electrical infrastructure at the mill. The economic scalability comparison between biogas and diesel-based systems is shown in Figures 7–9.

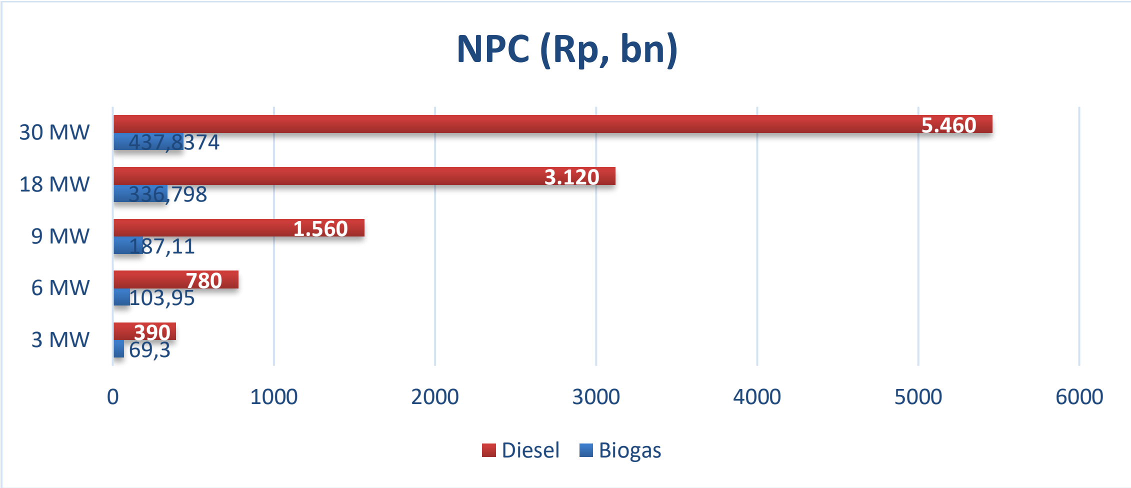


Figure 7. Net production cost comparison between diesel-based power generation system vis-à-vis biogas-based power generation system

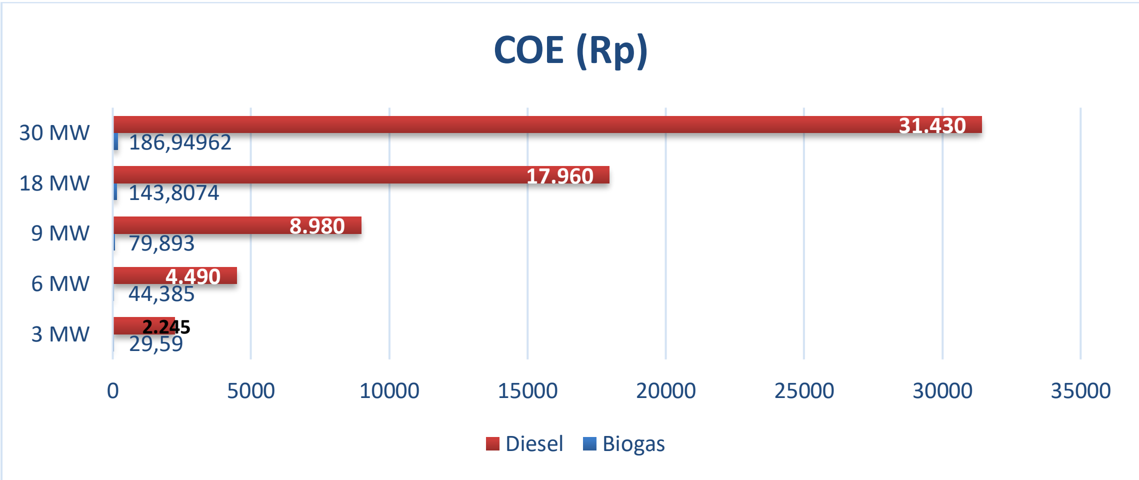


Figure 8. Cost of energy comparison between diesel-based power generation system vis-à-vis biogas-based power generation system

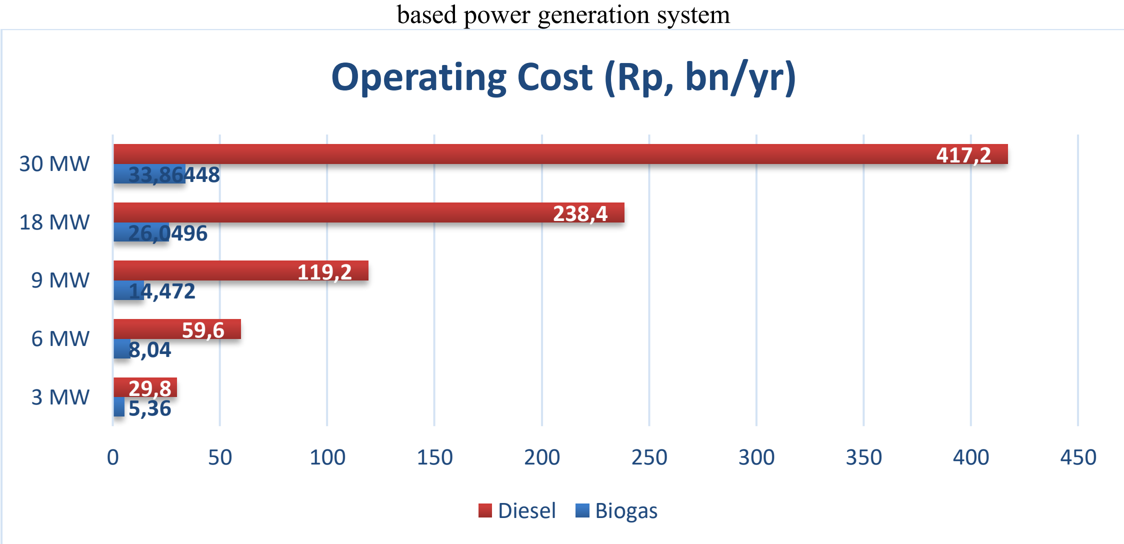


Figure 9. Operating cost comparison between diesel-based power generation system vis-à-vis biogas-based power generation system

Based on Figures 7 to 9, palm oil mill effluent biogas power plants can be expanded to accommodate higher power output at minimal cost due to the continuous availability of liquid waste. The availability of

POME is linearly related to biogas production, where more waste leads to higher biogas output through anaerobic fermentation. The organic content of POME, such as carbon and nitrogen, plays a key role in this process, producing methane-rich biogas. However, while this relationship is linear, factors such as temperature, pH, reactor capacity, and system design also affect biogas production efficiency. Maintaining optimal environmental and technical conditions is crucial for maximizing production efficiency, which impacts COE and NPC. Although biogas systems have high NPC, their COE is lower than diesel. Additionally, biogas systems are more scalable, requiring only minor expansions of the reservoir when increasing capacity, unlike diesel generators, which need additional fuel tanks for each new unit.

3.5. Technical Scalability Study

Scalability can be achieved in two ways:

1. Expanding generation capacity while maintaining the existing digester capacity. This scenario suits when increasing power-generating efficiency is the main consideration for power plant regeneration.
2. Expanding both generation capacity and digester facility capacity. This scenario is more suitable in multiple POMs when each POMs are approximately near each other and/or when implementing a centralized gasification facility.

These two approaches can be implemented flexibly, depending on plantation conditions, mill proximity, and regional characteristics. The scalability potential for both scenarios is illustrated in Figures 10–11.

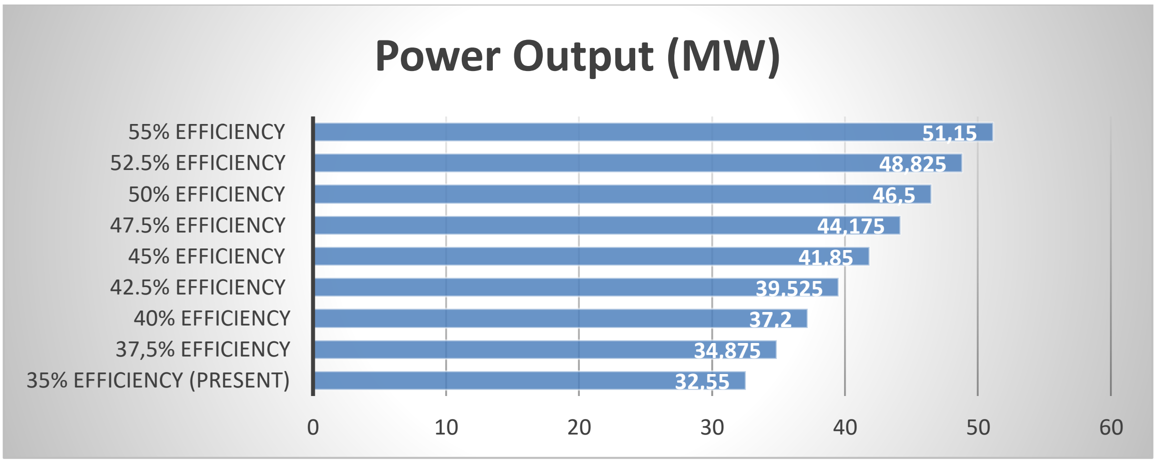


Figure 10. Scalability potential based on efficiency development increment without changing digester facility's capacity

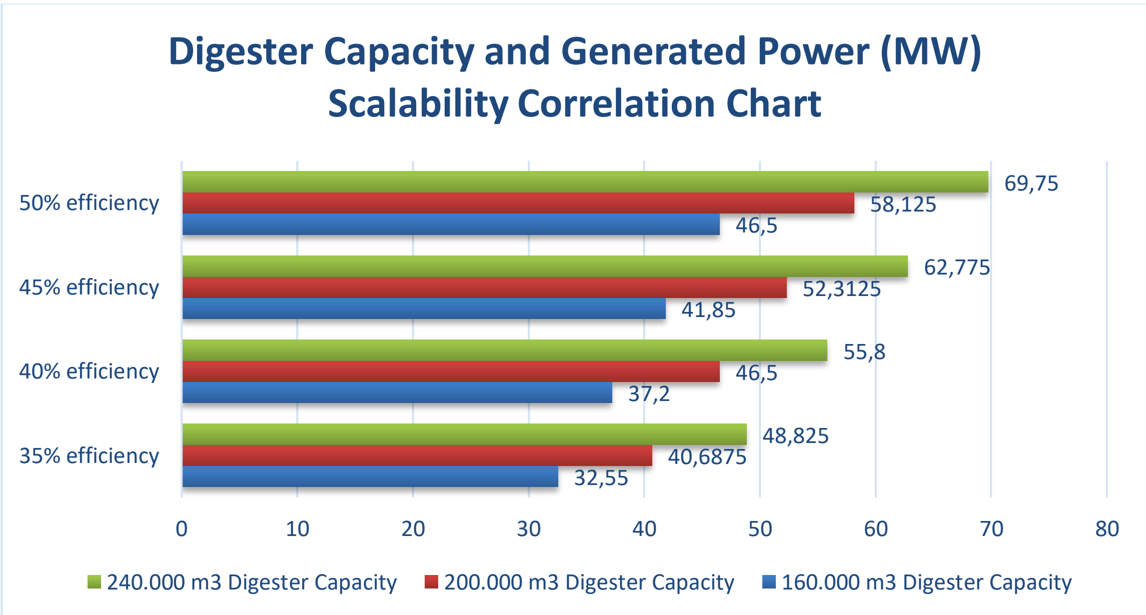


Figure 11. Scalability potential based on efficiency development increment in lieu of digester facility's capacity increment

Implementing either scenario can enhance power generation from palm oil mill effluent gasification while increasing Indonesia's renewable energy mix. This reduces reliance on fossil fuels, saving foreign exchange reserves and lowering emissions. Additionally, biogas power plants address POME waste management issues, reducing environmental pollution.

4. CONCLUSION

Based on the comparative simulation process between diesel power plants and biogas power plants to determine their scalability, several advantages were identified in using electricity from biogas power plants utilizing palm oil mill effluent (POME). The main advantages include higher energy efficiency, lower fuel costs, faster startup time—minimizing the impact on the thermal load controller (TLC)—and lower greenhouse gas emissions compared to diesel power plants, albeit with a relatively high initial investment cost.

Additionally, biogas power plants from POME can be developed in combination with other renewable power sources if needed. Apart from reducing the need for waste reservoirs, biogas enhances land productivity and reduces dependence on external fuels. On the other hand, it also offers significant scalability potential through several innovations, such as centralized digester systems with gas distribution networks or POME distribution networks, the use of larger-capacity gas engines, and biotechnological engineering in the gasification process of palm oil mill effluent.

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