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Biogas Power Generation from Palm Oil Mill Effluent (POME): Techno-Economic and Environmental Impact Evaluation

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Abstract: Using palm oil mill effluent (POME) to produce biogas is an alternative and sustainable way to control POME GHG emissions while also providing economic benefits. The increasing area of oil palm plantations encourages an increase in palm oil production and the generation of POME in Indonesia. This could increase potential GHG emissions and global warming. In contrast, biogas power plants from POME are less attractive for economic investment in Indonesia. However, as the world's largest palm oil producer, Indonesia still lacks techno-economic and environmental studies of biogas power generation from POME. This study aimed to evaluate the technical, economic, and environmental aspects of the biogas power generation from POME at the study site (Bangka Island, Indonesia). The result shows that the biogas plant at the study site can reduce COD levels of POME by up to 91% and produce biogas at 325,292 m^3/month, with a 55% methane content. Biogas can be converted into electrical energy at 696,163 kWh/month. The operation of this biogas plant can reduce GHG emissions by 1131 tons CO_2-eq/month, with low profitability (NPV of IDR—1,281,136,274, IRR 6.75%, and a payback period of 10.8 years). This evaluation proves that the main problem in the factory is the POME used, which is insufficient, and which could be overcome by purchasing POME from other palm oil mills. Furthermore, using the mesophilic anaerobic degradation process at the study site is feasible. However, a technological shift from closed lagoons to more efficient bioreactors is urgently needed, to increase the process efficiency and economic benefits.

Keywords: palm oil mill effluent; biogas; anaerobic process; power generation; GHG emissions; profitability

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1. Introduction

The yearly expansion of oil palm plantations in Indonesia is accompanied by an increase in the number of palm oil mills that produce crude palm oil (CPO) from fresh fruit bunches (FFB). The production process in a palm oil mill consists of sterilization, stripping, clarification, and palm kernel oil recovery [1]. This generates solid waste and liquid waste. This waste, when discharged directly into the environment without proper treatment, can pollute the environment, emitting greenhouse gases (GHG) that cause global warming. The composition of the waste produced by palm oil mills is mostly palm oil mill effluent [1,2]. Palm oil mill effluent (POME) is mostly generated from the stages of sterilization, clarification, and hydro-cyclone operation in palm oil mills [1]. Production of 1 ton of CPO requires about 5 to 7.5 tons of water, and nearly 50% of the water used ends up as POME [1]. POME contains very high levels of organic matter, such as a biochemical oxygen demand (BOD) of 8200–35,400 mg/L, chemical oxygen demand (COD) of 15,103–65,100 mg/L, and total solid (TS) of 16,580–94,106 mg/L [3]. Therefore, discharging it directly into the environment without appropriate treatment can cause various negative environmental impacts, such as water pollution and global warming.

POME with a high organic matter content has excellent energy potential to be utilized and developed [4]. The methane gas emitted by POME pollutes the atmosphere. However, it is very light and flammable, so it can be used as a fuel to replace natural gas, whose main component is methane. The utilization of biomethane or biogas has become widespread, both on an industrial and household scale, and efforts have even been made to transform natural gas-based domestic energy supplies into biomethane-based ones [5]. Biogas, which has a main component of methane gas, has been successfully produced through anaerobic POME processing, to control the environmental impact caused by POME. In earlier studies with an anaerobic digestion system, 1 m^3 of POME produced 28 m^3 of biogas, with a 65:35 methane level compared to carbon dioxide level [6,7]. A study of methane emissions from a commercial anaerobic pond system showed that for every kilogram of COD removed, 237 g of methane was emitted, which means 12.36 kg of methane/ton of POME is generated by the anaerobic pond system [6]. In another study, linear regression modeling prediction results showed that 909.76 m^3 of POME can produce biogas of around 34,489.70 m^3 [8]. The differences in the previous studies indicate that the anaerobic digestion of POME can produce biogas with different quantities and proportions of methane, depending on the processing technology and the characteristics of the POME used. The amount of methane that can be formed during anaerobic digestion is influenced by the characteristic of the raw material [9]. Biogas formed from the anaerobic digestion of POME usually has a methane composition above 50% [10].

Using POME to produce biogas is an alternative and sustainable way to control GHG emissions from POME, and can provide economic benefits. Digestate, as a by-product of the biogas production process, can also be used for bioremediation, as additives for animal feed, as a substrate for large-scale algae production, or as fertilizer [11]. Biogas is often used as a fuel to produce heat or electricity, but the production of heat and electricity simultaneously (co-generation) is considered more profitable [12]. In palm oil mills, biogas from POME can be utilized to meet the heat and electricity needs of the mill [13]. The use of biogas from POME that has been carried out to date in several palm oil mills in Indonesia has been for electricity generation, and then being sold or distributed to the grid of the national electricity company (NEC).

The process of generating electricity is strongly influenced by the quantity and quality of the used biogas [14]. Biogas with high quality has a high methane content and few impurities, so the energy contained in it is high. Therefore, the need for biogas to generate electricity will be less if the biogas is of high quality [14]. The impurity often found in biogas from POME is hydrogen sulfide (H_2S), which not only degrades the quality of biogas but can also cause corrosion of the generator engine. Reducing H_2S levels can increase engine life, providing long-term economic benefits [15]. The characteristics of POME strongly influence the quantity and quality of biogas produced from POME, as do the technical aspects of the biogas formation process, such as the pH, temperature, C/N ratio, type of pretreatment used [16], organic loading rate (OLR) and hydraulic retention time (HRT), acclimation and start-up, mixing, and biomass retention [13]. These technical aspects must be managed to optimize the biogas formation process, so that the quantity and quality of the biogas produced can be controlled. Figure 1 presents the process of biogas formation from organic compounds.

The stages of the conversion process of POME into biogas are essential to optimize the conditions of the biogas production process. Hydrolysis is the enzymatic breakdown of complex compounds (polymers) into simpler compounds (monomers), to facilitate the subsequent fermentation process [1,10,17]. At this stage, the reaction of complex compounds with water occurs. This hydrolysis process limits the biogas formation reaction rate, the duration of which depends on the size of the substrate being hydrolyzed [17]. Complex compounds such as carbohydrates, fats, and proteins are broken down into glucose, amino acids, and fatty acids, which are then decomposed further by acidogenic microbes to form carbon dioxide, hydrogen, ammonia, and volatile organic acids, such as acetic acid, propionic acid, lactic acid, and ethanol [18]. The reaction of the formed organic acids as intermediate products is part of a series of acidogenesis stages [1]. A lot of carbon dioxide and hydrogen are produced at the hydrolysis stage and during the formation of intermediate products.

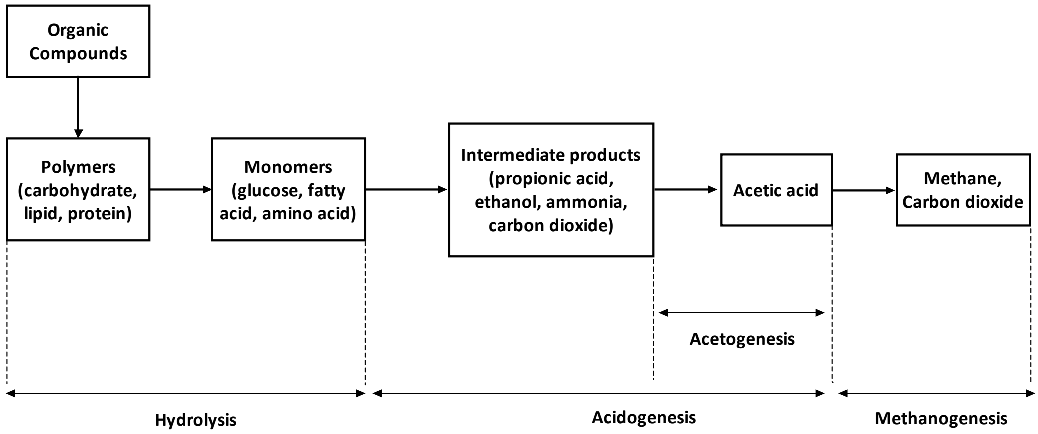

Figure 1. The conversion of organic compounds into biogas.

The intermediate product is converted to acetic acid at the acetogenesis stage by acetogenic microbes [1,10], and the carbon dioxide and hydrogen concentrations decrease. The conversion of acetic acid into methane and carbon dioxide occurs in the last stage (methanogenesis), as well as the conversion of hydrogen and carbon dioxide into methane and water by methanogenic microbes [7]. These methanogenic microbes are sensitive to pH, so the reaction can only run optimally in an pH range of 6.5–8 [1]. Methanogenic reactions in POME can produce more than 0.8 L of biogas per gram, with methane concentrations above 50% [10]. In addition, methanogenic microbes are also sensitive to temperature. Therefore, the type of microbes used will affect the operating temperature of the digester.

There are two operating temperatures for conventional anaerobic digesters: mesophilic, with a temperature range of 35–40 °C; and thermophilic, with a temperature range of 55–70 °C [13]. Mesophilic anaerobic processes have a higher performance stability than thermophilic anaerobic processes, characterized by a more diverse microbial community, but generally produce relatively lower biogas volumes [19]. This reason underlies the determination of the operating temperature of the digester.

Various studies have been conducted to study the technical-economic aspects of renewable energy utilization systems produced from waste. A techno-economic analysis was carried out in Turkey to determine the potential and economic feasibility of generating electricity in a biogas plant on a farm using an integrated sewage treatment system. The study results showed that the utilization of biogas produced in the combined heat and power unit was more profitable than the use of biogas in the combustion unit, which only produced heat [12]. This shows that co-generation systems are more economically profitable, while reducing greenhouse gas emissions [12]. A techno-economic analysis of electricity generation from biogas using palm oil waste in Malaysia showed that anaerobic digestion of POME to generate electricity was technically, financially, and economically feasible, with a shorter payback period if the capacity of the palm oil mill was more extensive [20]. The simulation of biogas capture from POME in Malaysia resulted in a palm oil mill with a capacity of 60 tons FFB/hour, which produces 234,000 m^3 POME per year and can generate 33,150 MWh/year of electricity, with a payback period of 4.3 years [21]. This indicates that utilizing POME for electricity in Malaysia is profitable and attractive. In Indonesia, Hasanudin et al. [2] estimated that a palm oil mill with a 45-ton FFB/hour capacity has the potential to generate about 0.95–1.52 MW of electricity and is capable of adding another 0.93 MW from anaerobic co-composting of empty fruit bunches (EFB). A co-generation system was also proposed by Hasanudin et al. [2], which utilizes POME and EFB together for producing renewable energy, compost, and liquid fertilizer. In line with Akbulut [12] and Hasanudin et al. [2], regarding a co-generation concept, Aziz and Kurniawan [22] proposed an integrated system for the use of POME and EFB to generate electricity based on heat circulation and energy efficiency. In the broader study area, namely Southeast Asia, the power generation potential from biomass residues comes from agricultural residues, with rice, sugarcane, and palm oil residues being the major contributors, while the highest energy potentials were located in Indonesia, Thailand, and Vietnam [23]. Furthermore, a techno-economic study was carried out at a 10 MW biomass-based power plant in Malaysia, which reported that increasing system efficiency could increase the cost savings when using mesocarp fiber [24]. In Indonesia, a techno-economic study for biogas power plants from POME was carried out using a simulation process and showed that biogas power plants from POME are feasible to build but less attractive as economic investments [25]. Recent techno-economic studies were carried out on a wind power production system along a coastal belt in Pakistan [26], a methane oxidation layer (MOL) in a landfill located in Seychelles [27], a biomass supply chain [28], and industrial-scale biodiesel production from POME [29].

As the world's largest producer and exporter of palm oil [30,31], Indonesia has an increasing area of oil palm plantations [31]. This encourages an increase in palm oil processing, and the generation of POME in Indonesia is also increasing. Increasing POME can increase the potential for GHG emissions, thus the global warming potential is also increasing. The increasing POME also indicates a high potential for biogas power generation from POME in Indonesia. In contrast to these conditions, biogas power plants from POME are less attractive as economic investments in Indonesia [25]. This can be caused by treatment processes that are not optimal or the application of technology that is not appropriate.

Various studies have been conducted to optimize biogas production from POME, to make it more profitable. Various bioreactor configurations have been studied to optimize biogas production [17], but their economic feasibility is not yet known. Various types of technology have also been studied to optimize biogas production from POME, especially technologies for POME pretreatment and co-substrates, which help increase biogas production [13]. Techno-economic analysis for biogas from POME as a compressed natural gas (Bio-CNG) has also been carried out in Malaysia, which showed that a biogas purification system with membrane separation technology has the lowest payback period value and, therefore, is the most economical [32]. These studies show the development of biogas production technology from POME, which is increasingly diverse. It provides many alternative technology options to optimize biogas production from POME, to be economically attractive and sustainable. However, the complex issues related to POME processing for renewable energy and environmental sustainability open the gap for further studies related to these techno-economic aspects.

Among the studies on the techno-economic aspects of the renewable energy utilization systems mentioned above, only a few have studied the use of POME for biogas production, which is used further for electricity generation. As the world's largest palm oil producer, Indonesia still lacks techno-economic studies of biogas power generation from POME. Although biogas production from POME is technically, economically, and environmentally promising, less than 10% of palm oil mills in Indonesia apply technology for biogas production from POME [30]. One of the palm oil mills in Indonesia that has produced biogas from POME and used it for electricity generation is in Bangka Island, which is the location of this study. The results of previous studies on biogas production from POME show that there are various alternative technologies to optimize biogas production from POME. This indicates a great potential to increase the sustainability of biogas power generation from POME, especially from the technical-economic-environmental perspective, making it more attractive for investment. Therefore, a techno-economic study was needed to evaluate the biogas power generation from POME in Indonesia, while considering environmental sustainability. This study aimed to evaluate the technical, economic, and environmental aspects of the biogas power generation from POME in the study site (Bangka Island, Indonesia). The results will help optimize the treatment processes of POME to generate electricity, making it more attractive and profitable for economic investment in Indonesia, while also reducing GHG emissions.

2. Materials and Methods

POME is a brown viscous colloidal material containing 95–96% water, 4–5% total solids (TS), including 2–4% TSS and 0.6–0.7% oil and fat, disposed of at 80–90 °C [2,33]. Almost all stages of the CPO production process in palm oil mills emit POME. The CPO production process in the mills requires large amounts of water, most of which will become POME. POME contains very high organic matter, because it comes into contact with organic matter in the CPO production process. This is supported by the measurements of POME characteristics by researchers in various studies. Based on the results of research conducted by Setiadi et al. [3], the measurement of POME characteristics of 28 palm oil industries belonging to PT Perkebunan (Indonesia) is presented in the Table 1.

Table 1. Characteristics of POME.

Parameter	Value
pH	3.3–4.6
BOD_5	8.200–35.400 mg/L
COD	15.103–65.100 mg/L
TS	16.580–94.106 mg/L
TSS	1.330–50.700 mg/L
NH_4-N	2.5–50 mg/L

Primary data collection was carried out by direct observation at the research site Bangka Island, Indonesia, supported by unstructured interviews. The primary data observation was taken for five days, and it was a one-time observation. The palm oil mill has an installed capacity of 30 tons of FFB/hour and utilizes all of the POME for biogas production to generate electricity. Secondary data were collected from the literature and related references. Cost components and material requirements for biogas production and electricity generation were estimated based on references and observations.

Based on previous studies, the biogas power generation technology from POME varies according to the availability and characteristics of raw materials and process conditions. Therefore, this affects the cost component in biogas production activities for electricity generation. Figure 2 presents a diagram of POME's electricity generation process; in general, processes commonly carried out in Indonesia. The generated electricity is transferred to the NEC grid (the national electricity company) for sale. Some palm oil mills use biogas fuel boilers instead of shells and other biomass. Digestate or bottom products are usually used for land application in oil palm plantations or in composting processes.

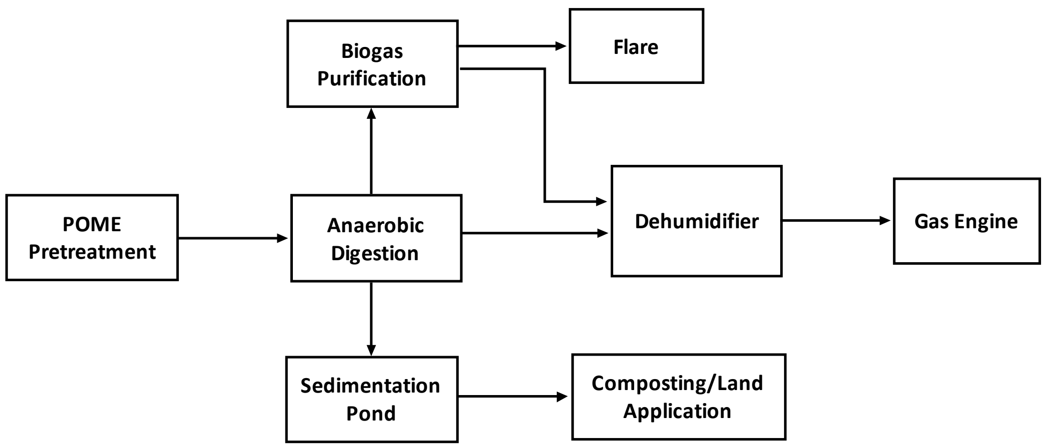

Figure 2. Process block diagram of biogas electricity generation from POME.

A techno-economic analysis was carried out quantitatively, adjusting to the biogas production process from POME, which was applied at the study site. A process flow diagram, total mass balance, and energy conversion diagram were used to help analyze the biogas production process from POME and the process efficiency. With the energy conversion diagram, the heat loss can be calculated, so that energy conversion efficiency can also be known. In addition, the potential energy in the biogas and energy consumed for electricity generation were analyzed. Previous studies have also applied mass or energy balance to analyze the anaerobic digestion system to produce renewable energy. For example, this method has been applied to study the anaerobic digestion for domestic food waste [34], anaerobic digestion to produce biogas from industrial waste [35], anaerobic digestion in the rice–wine–pig system [36], and anaerobic digestion to produce biogas from microalgae [37]. Furthermore, mass or energy balances make it possible to evaluate the bioconversion efficiency carried out by microbes, to convert complex organic substrates [38].

An economic evaluation was carried out by calculating the profitability. The profitability value can be calculated by various methods, including calculating the rate of return on investment (ROI), discounted cash flow, net present value (NPV), costs for capital, and payout (payback) period [39]. The profitability evaluation in this study was carried out by calculating the NPV, internal rate of return (IRR), and payback period. The GHG emissions calculation was also carried out based on calculations that refer to the Intergovernmental Panel on Climate Change (IPCC) guide. GHG emissions have been widely used as a sustainability indicator of renewable energy systems, by various previous studies [40–44]. This is closely related to the issue of global warming. The GHG emissions taken into account in this study consisted of biogas combustion emissions, fugitive emissions, electricity generation emissions, and final waste emissions in the pond system [45,46].

3. Results and Discussion

3.1. Process Description

The following block diagram (Figure 3) illustrates the biogas production process using covered lagoon technology to generate electricity at the study site.

POME is channeled to the feeding pit, which functions as a temporary POME reservoir, before flowing to the cooling tower. POME is fed to the buffer pond if the digester does not require feeding. The cooling tower reduces the temperature of the POME, which is still hot (70–90 °C) when it leaves the palm oil mill, until it reaches a temperature of 30–40 °C. This pretreatment is necessary because the bacteria used are mesophilic and cannot function well at high temperatures. The POME from the cooling tower goes to the distribution pond and then enters the digester. The digester used is a covered lagoon with a geomembrane layer. Anaerobic degradation occurs in the digester, resulting in organic compounds' conversion into biogas through hydrolysis, acidogenesis, acetogenesis, and methanogenesis, as shown in Figure 3. The average HRT in the digester is 20–30 days. To overcome the accumulation of solid deposits at the bottom of the digester, mixing POME in the digester is carried out with the reflux flow. POME recirculation is carried out with the help of a distribution pond, to adjust the bacterial conditions and pH in the digester.

The bottom product of the digester in the settling pond that has undergone sedimentation is flowed into anaerobic ponds and is left for about one month, and then used for plantation land applications. The digester's light product (biogas) flows to the scrubber to be purified from hydrogen sulfide gas (H_2S) through the absorption of H_2S by water. The water used as absorbent comes from the settling pond. The water used in the scrubber flows into the circulation pond, then to anaerobic ponds, and is mixed with the final effluent to be used for land applications. Biogas from the wet scrubber is channeled to the dry filter, to clean the biogas of other remaining impurities. The dry filter utilizes solid waste (shell and FFB fiber) from palm oil mills as a filter. Biogas from the dry filter flows to the heat exchanger (HE), to be cooled by a heat transfer process. Biogas from the HE goes to a generator with a capacity of 2000 kW, to be used as fuel and converted into electrical energy. Biogas flows to the flare or the digester during engine maintenance.

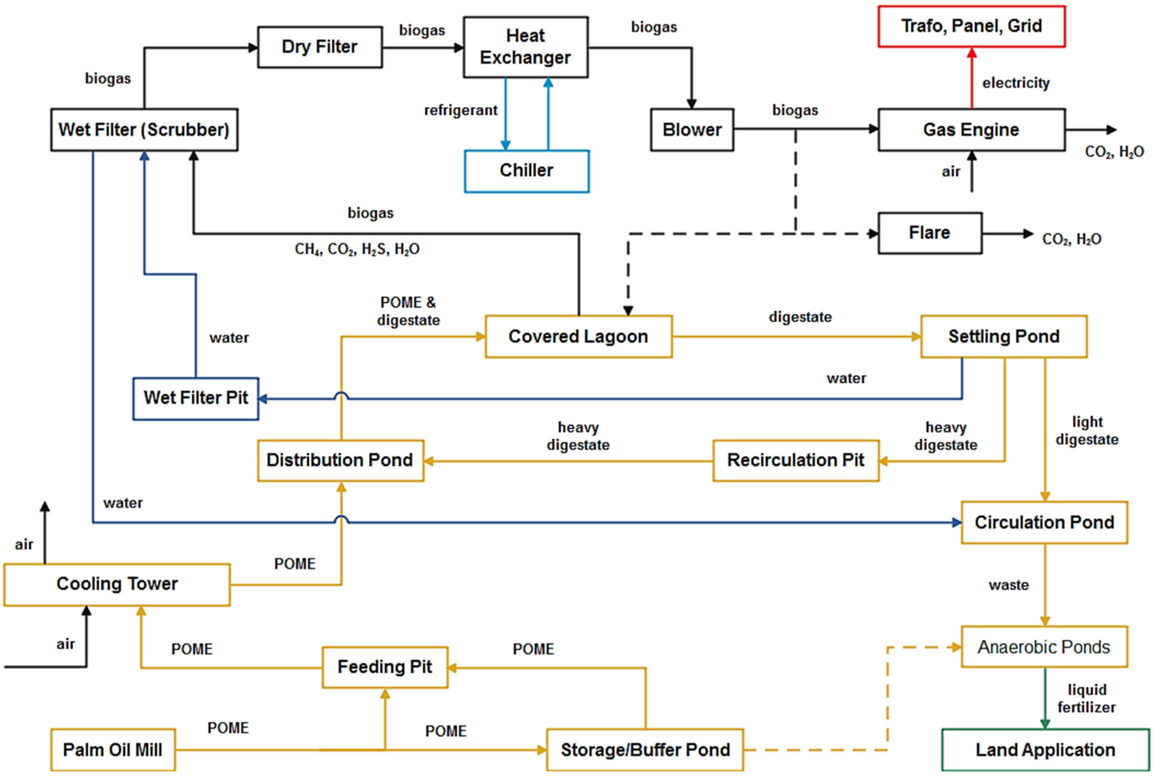

Figure 3. Block flow diagram of a biogas plant to generate electricity, based on the observation results.

Based on the process described above, it can be seen that this mill applies a conventional biogas production system, as do most other palm oil mills in Indonesia. A closed lagoon is used to capture methane gas as a modified form of the pond system. This type of digester has a large capacity, requires a large area of land, is easier to operate than other types, and does not require a highly skilled workforce. Before implementing methane capture technology, this plant treated POME with a pond system consisting of a series of anaerobic and aerobic ponds. The pond system used at the study site has undergone several modifications, including the application of mixing by periodically flowing a reflux current. One of these mixing functions is to reduce the accumulation of solids at the bottom of the pond. Pond systems tend to lack mechanical agitation, operational control, and monitoring [47]; require a large area of land to accommodate a series of ponds; increase foaming in the surface area of POME; and increase solids at the bottom of the pond, which reduce the treatment efficiency [1].

In conventional systems, higher methane release rates occur in anaerobic pond systems than in open tank systems [47]. A closed anaerobic pond allows anaerobic microbes to work more optimally. This explains how a pond system can produce more methane than an open tank system. Although less methane is produced in an open tank system, the process is continuous, and the solids at the bottom of the tank can be cleaned regularly and used as fertilizer [1]. In addition, a tank system does not require a large area of land, and the HRT is shorter (20 to 25 days) than in a pond system [1]. The disadvantage of the tank system is that the tank material is easily corroded, and there is a risk of an accidental tank bursting or collapsing [6]. This corrosion can be overcome by using a tank made of corrosion-resistant metal, such as stainless steel, but this can create new problems related to costs and a very high investment due to the high price of the tank.

The biogas plant in the study site prioritizes the stability of the performance of the biogas formation process; thus, it is operated at mesophilic temperatures. In addition, although the thermophilic process can achieve higher organic matter degradation, it is often hampered by the accumulation of volatile fatty acids (VFA) and other toxic substances, which increase with increasing temperatures above 60 °C [48]. Thermophilic anaerobic degradation has the advantage of a higher digester capacity with more biogas production but lower removal of chemical oxygen demand (COD) than mesophilic biodigesters [49]. In addition, the thermophilic process produces slightly lower methane levels in the biogas produced compared to the mesophilic process [48]. Thus, the mesophilic process is more suitable for process stability, the reduction of COD levels in the effluent, and the quality of biogas, although the quantity of biogas obtained is smaller than that of the thermophilic process.

As it is more effective in reducing COD levels in sewage, the mesophilic process of HRT is shorter than the thermophilic process. Therefore, the anaerobic degradation rate strongly influences the HRT in the digester. The rate of biogas formation is proportional to the rate of reduction of the concentration of the substrate used, which can be approximated by the reduction of COD levels in POME. The reaction rate of biogas formation follows the first-order reaction model [50], which is as follows:

$$\begin{aligned} \frac{dC}{dt} &= -kt \\ ln\frac{C_0}{C_t} &= kt \end{aligned} \quad (1)$$

C_0 is the initial reactant concentration (COD), C_t is the reactant concentration (COD) at the time of t, and k is the reaction rate constant. The average COD level in POME at the study site was 57,673 mg/L, while the COD level in digestate was 5254 mg/L. Based on the above equation, with the same reaction rate constant, and to achieve the exact COD conversion, the mesophilic process requires a shorter HRT than the thermophilic process because the process performance is more stable (faster). Dilution and stirring of POME can also help the process stability in the digester because the homogeneity of the solution is maintained, so that the bacteria can work better.

Regarding the stages of biogas formation, the hydrolysis and methanogenesis stages require more attention, so that the conversion process runs smoothly. The hydrolysis step controls the overall reaction rate, because it takes the longest time to break down organic polymer compounds. If the POME is too thick, this problem can be helped by dilution. The methanogenesis stage requires certain conditions to keep the methanogenic microbes alive, so it is necessary to adjust the reaction conditions, such as the pH and digester temperature, which must be kept stable. The characteristics of the substrate and the operating conditions are considered in various types of technology for biogas production. The following table (Table 2) gives some advantages and disadvantages of the conventional pond systems applied at the study site.

Table 2. Advantages and disadvantages of conventional pond systems.

Advantages	Disadvantages	References
▪ Less capital required ▪ It can be used for processes with a high OLR ▪ Simpler maintenance (does not require much maintenance) ▪ Fewer energy requirements and stable	▪ Requires a large area ▪ The HRT may be longer ▪ Accumulation of solids/sludge at the bottom of the pond ▪ Higher contribution of GHG emissions related to the use of multiple ponds (not all ponds are covered) ▪ Inefficient in reducing high levels of nutrients in waste	[6,51]

Biogas production with a closed lagoon system or by capturing biogas from an anaerobic pond (methane capture) is preferred in Indonesia, because of its low capital, practicality, and high OLR, so that it can process large amounts of POME. Although large areas of land are available for pond system installation, pond systems tend to require a long HRT, are inefficient in reducing COD levels, and contribute significantly to GHG emissions, due to the use of several large ponds. Thus, from an environmental sustainability point of view, using pond systems for biogas production from POME has a more significant negative impact than other types.

3.2. Total Mass Balance and Efficiency of Energy Conversion

The total mass flow calculated in this study was simplified to the mass entering the biogas production system, minus the mass leaving the system. Based on the process description, the mass flow into the system consists of POME, while that leaving the system consists of biogas, digestate, and used absorbent. The biogas leaving the system consists of biogas for electricity production and biogas that is burned directly in the flare. Based on simplifying the block flow diagram in Figure 3 and the data from the study site, the total mass balance can be presented as Figure 4:

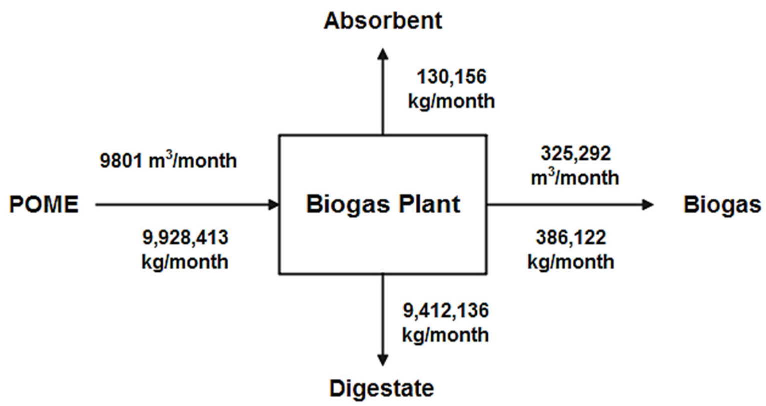

Figure 4. The total mass balance.

Based on the total mass balance above, the amount of POME degraded into biogas, used for absorbent, and that becomes digestate used for land application can be known. About 95% of POME becomes digestate, which is stored in open ponds. The digestate has a much lower COD content than POME, because most organic matter has been degraded into biogas.

The mass balance calculation above becomes the basis for calculating the energy conversion efficiency in the system, as presented in Figure 5. The heat capacity of POME is approximated to the value of 2030.11 kJ/kg [52]. The density of methane gas is estimated by a calculation according to the gas conditions at a temperature of 30 °C and a pressure of 1 atm, to obtain a value of 0.65 kg/m^3 [53,54], while the density of biogas is estimated using a value of 1.187 kg/m^3 [55]. The energy value of methane gas is estimated at 35.7 MJ/m^3 (based on the calculation used in the plant and interview results). The energy value of biogas is calculated based on its methane composition.

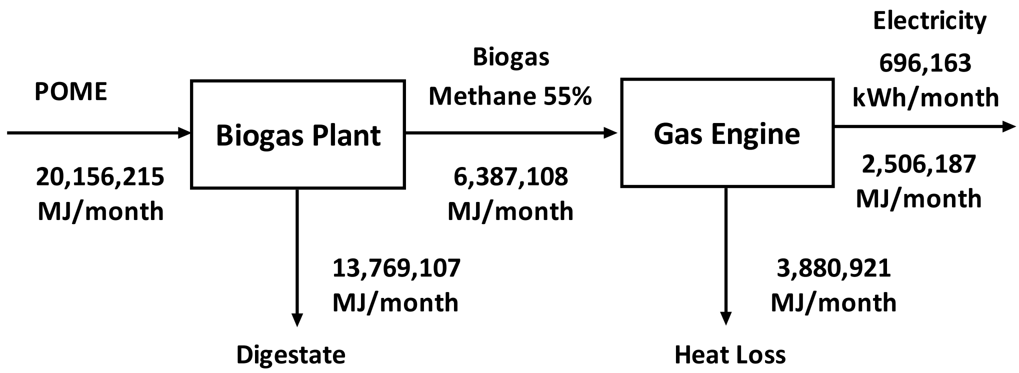

Figure 5. Energy conversion in the system.

The calculation results show that POME of 9801 m^3/month containing 20,156,215 MJ/month of energy can produce biogas with an energy content of 6,387,108 MJ/month. The amount of energy converted into electrical energy depends on the efficiency of the generating unit. Based on Figure 5 above, the efficiency of energy conversion from POME into electrical energy can be calculated, which is 12.43%. This value is higher than the simulation by Chin et al. [21] for a biogas plant in Malaysia, which also uses a conventional anaerobic system. Based on the simulation, 1,105,000 kWh/month of electricity is generated from a POME of 19,500 m^3/month. With the same assumptions, these conditions indicate an efficiency of POME conversion to electrical energy of 9.92%. The higher energy conversion at the research site was due to the higher COD content in POME compared to the POME used in Chin et al.'s simulations. Therefore, this proves that the characteristics of the POME also determine the electrical energy conversion achieved.

Based on the Figure 5, various alternatives can increase the electricity production, including minimizing heat loss and maximizing the biogas production. It is clear that the energy conversion is influenced by, among other aspects, the efficiency of the generator engine used, the quantity and quality of biogas produced and used for electricity generation, and the conversion process of POME into biogas. The engine's efficiency is an inherent characteristic, which is difficult to increase except by replacing the engine with another whose specifications can provide a greater efficiency in the conversion. Thus, this study only discusses the factors of the process of POME into biogas that affect the quantity and quality of biogas, as stated by Firdaus et al. [14].

The conversion of POME into biogas (Figure 1) consists of the stages of hydrolysis, acidogenesis, acetogenesis, and methanogenesis, all of which occur in the digester. The POME comes from a nearby palm oil mill with a high water content, thus accelerating hydrolysis. Moisture content critically controls the mass transfer and dissolution of organic matter in the digester, but if the substrate contains a lot of solids, the process will face many obstacles [13]. Thus, a high water content in POME is favorable for the substrate degradation process, especially at the hydrolysis stage. However, the POME still requires a pretreatment process with a cooling tower, to lower the temperature to make it suitable for the mesophilic process. The mesophilic process is very beneficial for the methanogenesis stage and is appropriate to be applied in a biogas plant for performance stability [19].

With an electricity demand from the NEC of 10,512 MWh/year or 876 MWh/month, the biogas production process to generate electricity that has been implemented so far has not been able to meet this demand. The biogas plant is estimated to need 180,000 m^3 of POME per year. The palm oil mill that supplies POME for the biogas plant has a capacity of 30 tons of FFB/hour. Each ton of FFB processed in the palm oil mill is estimated to produce 0.75 m^3 of POME. With a yield of 25% [2], 1 ton of processed FFB can produce 0.25 tons of CPO. The production of 1 ton of CPO requires about 5–7.5 tons of water, and more than 50% of that water ends up as POME [1]. The palm oil mill would need to operate for more than 20 h per day to meet these POME requirements, but in reality, the mill only operates an average of 17 h per day. Based on historical data for three years (2018 to 2020), the operating time of palm oil mills ranges from 93 to 676 h/month. The operation time of this mill is highly dependent on the availability of FFB raw materials, most of which are supplied from FFB produced by community plantations. Based on these conditions, it can be seen that the limited amount of POME that is processed is the main obstacle that can cause the biogas production not to be as expected. This can be solved in various ways, such as by increasing the palm oil mill's operating capacity, empowering communities to sell FFB to the mill, or by purchasing POME from other palm oil mills.

The need for raw materials for biogas could be met with a POME input of 180,000 m^3 per year or 15,000 m^3 per month, which could be achieved by increasing the capacity of the palm oil mill or buying POME from other mills. However, increasing the capacity of a palm oil mill means increasing investment costs and requires an increasing number of FFB. Moreover, the area of oil palm plantations owned by this company is limited. To date, the fulfillment of FFB needs for the mills has mainly been supplied from community plantations; and even then, the mill is not operating optimally. Thus, increasing the capacity of the palm oil mill is not practical. On the other hand, the number of palm oil mills on Bangka Island that processes POME into biogas and electricity is still limited, so it is possible to increase the availability of POME by purchasing from other mills.

If the adjustable POME is 15,000 m^3/month, then with the same POME characteristics, it is estimated that it could produce as much as 498 m^3/month of biogas. With a methane content in biogas of 55% and the same power generation efficiency, the electricity that could be generated is 1059 MWh/month. A comparison of this scenario with business-as-usual conditions is presented in the Table 3.

Table 3. Technical comparison of two POME sufficiency scenarios.

	Business-as-Usual	**Sufficient POME**
POME used (m^3/month)	9801	15,000
POME energy (MJ/month)	20,156,215	30,847,521
Biogas produced (m^3/month)	325,292	497,834
Methane content	55%	55%
Biogas energy (MJ/month)	6,387,108	9,774,973
Gas Engine efficiency	39%	39%
Electricity generated (kWh/month)	696,163	1,058,955
Electricity generated (MJ/month)	2,506,187	3,812,239
Energy needs to operate biogas plant (kWh/month)	34,808	52,948
Efficiency of energy conversion	12.43%	12.36%

Adding POME by purchasing it from another plant, without increasing the installed capacity, will automatically increase the biogas production and electricity generation. The electricity requirement for the biogas plant operation is estimated at 5% of the electricity generated. Thus, the greater the electricity generated, the greater the energy needed for operations. Table 3 also shows that the efficiency of converting electrical energy with sufficient POME is slightly lower than the business-as-usual conditions. Furthermore, by comparing the changes in the output of electrical energy with the input of POME, the result is that each addition of 1 m^3 of POME can add 251.21 MJ of electrical energy.

Biogas with a high methane content is expected to produce large amounts of energy. From the point of view of waste processing, a high COD conversion is also expected. Thus, these two parameters can be used to determine the quality of the anaerobic digestion to produce biogas, namely methane content and COD conversion. Technological innovations can affect the process efficiency in the plant. An efficient process can produce higher energy levels, even when using limited POME. With the application of technology that can achieve a higher COD conversion and methane content, the energy content in biogas could be increased, and electricity production could also be increased.

3.3. GHG Emission and Environmental Impact

Based on the process described above, it can be seen that this plant utilizes solid and liquid waste from palm oil mills for the production process, such as for water absorbers in the scrubber tower and filter media in dry filters. Using palm oil mill waste for processing purposes in the plant is very beneficial for environmental sustainability and for saving expenses in plant operations. The plant also uses palm oil mill solid waste for composting separately (not integrated with the biogas production). This shows that the co-generation concept has not been fully implemented in this plant, thus affecting the overall process efficiency. The composting process could save water use by utilizing the bottom product of the digester and can be carried out together with biogas production, as has been proposed by Hasanudin et al. [2]. In addition, wasted heat could also be implemented, to minimize energy losses.

The biogas plant's digestate (bottom product) is used for plantation land applications, as a fertilizer. The COD levels in the digestate are not as high as the COD levels in POME before being processed into biogas, so that the GHG emissions are not too large. The negative impact of POME, which is quite significant, is in GHG emissions that cause global warming. Thus, using biogas from POME for electricity generation can reduce these emissions. The GHG emissions of the biogas plant in the study site can be presented according to the following results (Table 4). The calculated GHG emissions are methane gas with a global warming potential (GWP) value of 21-times the GWP value of carbon dioxide.

Table 4. Benefits of reducing GHG emissions with a biogas plant.

POME emission without biogas plant (baseline emission)	1920 tCO_2-eq/month
Combustion emission	244 tCO_2-eq/month
Fugitive emission	242 tCO_2-eq/month
Wastewater emission	220 tCO_2-eq/month
Emission from electricity generation	84 tCO_2-eq/month
Total biogas plant emission	790 tCO_2-eq/month
Emission reduction	1131 tCO_2-eq/month

Values were entered based on the average values, according to operational conditions in 2018–2020. In the table above, the operation of a biogas plant can significantly reduce POME GHG emissions, in this case, by 1131 tCO_2-eq/month. Therefore, it is beneficial for environmental sustainability.

3.4. Profitability Evaluation

The biogas plant in the study site sells electricity to the NEC under a contract at a fixed price for 20 years. The factory will receive a penalty fee if the electricity sales are below the targeted demand. The following (Table 5) is the biogas plant cash flow for 2018–2020 based on interviews and calculations.

Table 5. Biogas plant's cashflow from 2018 to 2020.

Year	0	1	2	3
Investment (IDR)	63,500,000,000			
Operational cost (IDR)		3,115,176,560	1,988,473,440	3,807,236,000
Electricity demand (kWh)		10,512,000	10,512,000	10,512,000
Sales (kWh)		7,787,941	4,971,184	9,518,090
Selling price (IDR/kWh)		1575	1575	1575
Penalty fee (IDR)		3,178,588,639	4,126,945,833	1,417,398,840
Revenue (IDR)		12,266,007,705	7,829,614,170	14,990,991,750
Cashflow (IDR)	(63,500,000,000)	5,072,242,506	814,194,897	8,866,356,910

The following (Table 6) is the result of evaluating the profitability of the biogas plant in the study area, by calculating the NPV and IRR. In addition, the cash flow in subsequent years during the plant's life (20 years) was estimated based on the average cash flow for 2018–2020.

Table 6. Profitability evaluation of the biogas plant.

Indicators	Value
Interest rate	7%
NPV (IDR)	(−1,281,136,274)
IRR	6.75%
Payback period	10.8 years

Based on the evaluation results above, it can be estimated that over the operational life of the biogas plant, this plant can generate a profit with an IRR of 6.75%, lower than the interest rate. The payback period of 10.8 years is too long compared to the payback period of biogas plants in Malaysia of 4.3 years [21]. A negative NPV indicates that this investment is not profitable, and will even causes the company to lose money. This shows that the current operating conditions of the plant are at risk of experiencing losses if sales cannot be increased. This condition is in line with Gozan et al. [25] in their study. Table 7 compares the electricity generation from POME at the study site and that simulated by Chin et al. [21] in Malaysia.

Table 7. Comparison of two electricity generations.

	Study Site (Bangka Indonesia)	**Simulation by Chin et al. [21]**
Palm oil mill capacity	30 tons FFB/hour	60 tons FFB/hour
POME generated	138,952 m^3/year	234,000 m^3/year
Power plant capacity	2 MW	1.66 MW
Electricity generated	8,353,956 kWh/year	13,260,000 kWh/year
Operational costs	4,241,582,250 IDR/year	2,458,404,000 IDR/year
Electricity sales	11,695,537,875 IDR/year	16,717,147,200 IDR/year (IDR 1 = RM 3708)
Payback period	10.8 years	4.3 years

Based on the evaluation results, the main problem of low profitability is the low electricity generated, which is 8354 MWh/year, while the demand from the NEC is 10,512 MWh/year. In the previous discussion, one of the alternatives to increase electricity production was increasing the amount of POME that is processed. The availability of this POME can be increased by purchasing POME from other palm oil mills or by increasing the capacity of the palm oil mills. This condition supports the results of research by Begum and Saad [20], where a shorter payback period can be achieved if the capacity of the palm oil mill is larger than before. This also explains why this biogas plant has a meager profitability, due to the small capacity of the palm oil mill (30 tons of FFB per hour), and does not operate optimally. Thus, buying POME from other palm oil mills is recommended, to increase the amount of POME processed, as discussed in Section 3.2.

Table 8 compares the profitability of the business-as-usual conditions and sufficient POME conditions. It can be seen that the scenario of purchasing POME from other mills could meet the demand for electrical energy from NEC and increase the profitability of the plant, even though the operational costs would increase. The increase in operating costs is mainly due to increased operating hours, energy used, equipment maintenance, and additional costs for purchasing POME (estimated at 10 IDR/m^3 POME).

Table 8. Profitability comparison of the two scenarios.

	Business-as-Usual	**Sufficient POME**
POME used (m^3/year)	117,612	180,000
Operational costs (IDR/year)	4,241,582,250	5,983,609,639
Electricity sales (kWh/year)	8,353,956	12,707,464
Penalty fee (IDR/year)	2,701,144,020	0
NPV (IDR)	−1,281,136,274	61,009,171,687
IRR	6.75%	15.72%
Payback period (years)	10.8	6.5
Interest rate	7%	7%

Table 7 also shows that the operational costs at the study site are higher than the operating costs at the biogas plant simulated by Chin et al. [21]. This indicates an inefficient production process in the plant. Increasing the process efficiency can increase the quantity and quality of biogas, so it contains higher methane levels than before. Higher methane levels in biogas can help increase the electrical energy generated. In this case, applying more efficient process technology is highly recommended. This is in line with the statement of Malek et al. [24], that increasing system efficiency could increase cost savings. Substituting technology with a more efficient one will increase the investment costs but this can be balanced by increasing profits. This shows that technological interventions are very influential on company profitability.

4. Conclusions

Environmental impact evaluation shows that POME in the study site has the potential to emit 1920 tons CO_2-eq/month. However, the biogas installation at the study site reduced GHG emissions by 1131 tons CO_2-eq/month from POME. This is beneficial for environmental sustainability; thus, biogas production from POME needs to be widely applied in other palm oil mills. Based on the techno-economic evaluations, it can be concluded that the biogas plant in the study site has a low profitability, with a NPV of IDR (−1,281,136,274), IRR value of 6.75%, and a payback period of 10.8 years. Our result explains why the biogas power plants from POME are less attractive for economic investment in Indonesia. Therefore, this requires improvement of the existing processes in the plant. Some suggested solutions are to apply the concept of co-generation, which is integration between CPO production, biogas production, composting, and electricity generation, so that the process runs more efficiently. In addition, applying more efficient biogas production technology is highly recommended, to increase the quantity and quality of biogas. Furthermore, the availability of POME for biogas production is suggested to be increased, by purchasing POME from other palm oil mills, especially those with larger capacities.

The covered lagoon technology for biogas production, which is a modification of the pond system, is prevalent in palm oil mills in Indonesia. This is mainly because the investment costs are low and do not require highly skilled human resources. Thus, it is necessary to upgrade the biogas production technology in Indonesia. In addition, government intervention is needed, regarding policies of biogas production from POME for electricity generation. With government intervention, using POME for biogas production and electricity generation could be scaled up and applied to more palm oil companies in Indonesia.

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