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UTILIZATION OF PALM OIL MILL LIQUID WASTE (POME) AS AN ALTERNATIVE FUEL BIO COMPAC NATURAL GAS OR BIO-CNG

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Abstract

Indonesia faces crucial challenges in energy security due to the increasingly alarming decline in oil reserves from around 3.6 billion barrels in 2000 to less than 2.5 billion barrels in 2023, while dependence on oil imports continues to burden the national energy balance and economy. Amid unstable global geopolitical conditions, including the Russia-Ukraine war and tensions in the Middle East that have caused fluctuating energy prices, the transition to local and sustainable energy sources has become a strategic priority. The Indonesian government has affirmed its commitment to achieving net-zero emissions by 2060 through various energy transition policies, including the development of renewable gas and the utilization of waste as an energy source. One of the major potentials that has not been optimally utilized is palm oil mill effluent (POME), which annually produces more than 500 million tons throughout Indonesia. POME contains a high concentration of organic matter that can be processed through anaerobic digestion to produce biogas, which is then purified and compressed into Bio-Compact Natural Gas (Bio-CNG). This study analyzes the potential of Bio-CNG technology from POME in three main dimensions: (1) conversion and storage technology, (2) economic analysis and feasibility of scale implementation at the palm oil mill level, and (3) its contribution to reducing GHG emissions and diversifying national energy. The study results show that by utilizing 70% of the total annual POME, the potential for Bio-CNG production reaches over 3.5 billion m³/year, equivalent to over 25% of current domestic natural gas consumption. Furthermore, the application of this technology can reduce CH3 emissions.$_4$from POME waste up to 80% and contributes significantly to the target of renewable energy (EBT) mix of 23% in 2025 and net zero in 2060. Economically, Bio-CNG shows competitive production costs (Rp25,000–35,000/m³) compared to industrial gas prices, especially with the presence of carbon incentives and carbon pricing mechanisms that are being developed. This study concludes that converting POME into Bio-CNG is not only a green technology solution but also a crucial energy security and climate mitigation strategy amidst uncertain global energy supplies and international decarbonization pressures. Policy recommendations include tax incentives, integration into the national gas grid, and mandatory regulation of waste energy utilization for the palm oil industry.

Keywords :Bio-CNG, POME, renewable energy, energy security, net zero emission

INTRODUCTION

Indonesia faces complex energy challenges in the 21st century. Declining oil reserves, from approximately 3.6 billion barrels in 2000 to less than 2.5 billion barrels in 2023, have directly impacted the country's status as a net oil importer since 2003. Dependence on oil imports not only threatens national energy security but also makes the economy vulnerable to global price fluctuations, exacerbated by geopolitical instability, such as the Russia-Ukraine war and tensions in the Middle East. In this context, energy diversification based on local resources becomes a strategic imperative.(Parmansyah et al., 2024).On the other hand, Indonesia's commitment to the Paris Agreement and the Long-Term Low Carbon Development Strategy (LTS-LCD) plan affirms the target of net zero emissions by 2060. To achieve this, the energy sector must undergo a major transformation, including increasing the mix of new and renewable energy (EBT) from around 13% in 2023 to 23% in 2025 and continuing to increase until achieving full decarbonization in the next few decades. One promising solution is the use of renewable gas energy, particularly Bio-Compact Natural Gas (Bio-CNG) produced from organic waste.(Zul et al., 2024). Indonesia, as the world's largest palm oil producer, produces more than 500 million tons of palm oil mill effluent (POME) annually. POME contains a high organic load (COD 20,000–60,000 mg/L), which, if left untreated, can become a source of methane (CH) emissions.$_4$) greenhouse gases with a global warming potential of 28–34 times higher than CO_2However, this potential can be harnessed through the anaerobic digestion process to produce biogas, which is then purified and compressed into Bio-CNG, ready to use as an alternative fuel for transportation, industry, or power generation.(Abdul Salim Jasman, 2023). Despite the enormous potential of this technology, its utilization remains very limited due to technological, economic, and regulatory constraints. This study aims to analyze the technical, economic, and environmental potential of converting POME to Bio-CNG, as well as its role in supporting national energy security and achieving the 2060 net-zero emission target. By integrating POME production data, energy consumption profiles, and energy policy projections, this study is expected to provide a scientific basis for policy development and investment in sustainable energy systems based on waste.(Irwan, 2021).

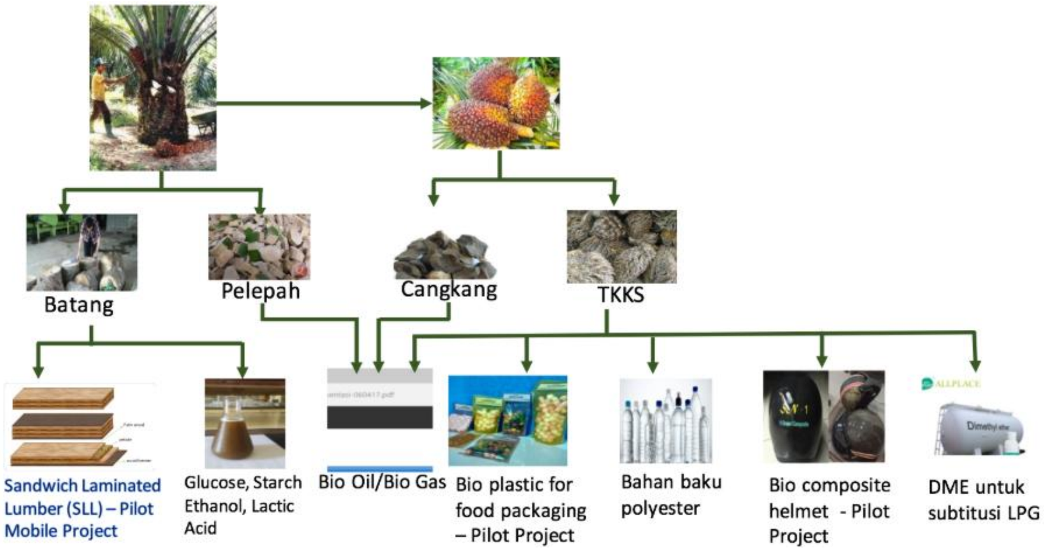
LITERATURE REVIEW

National and Global Tension Conditions

The global energy crisis has become a major concern for many countries, including Indonesia. The world's dwindling oil reserves are predicted to last only about 50 years at current consumption rates. Indonesia, which was a member of OPEC in the 1960s, has been a net oil importer since 2003. The latest data shows that Indonesia's oil reserves are only around 2.4 billion barrels, with production continuing to decline.(Bakar et al., 2022)Global geopolitical instability is further threatening national energy security. The conflict in Ukraine, tensions in the Middle East, and competition between major powers have led to extreme oil price volatility. Global crude oil prices, which reached $120 per barrel in 2022, are putting severe pressure on Indonesia's trade balance and energy budget. To address this challenge, the Indonesian government has set a target for a renewable energy mix of 23% by 2025 and 31% by 2050. This commitment is further strengthened by the net-zero emissions target by 2060 through the Long-Term Low Carbon Development Strategy (LTS-LCD). One sector with significant potential to support this target is the bioenergy sector, specifically biogas and Bio-CNG from agricultural and plantation waste.(Dirt et al., 2022).

Biomass Potential in Indonesia

Indonesia has enormous biomass potential due to its geographical conditions and tropical climate. Biomass from agricultural waste such as rice husks, empty oil palm fruit bunches, and sugarcane bagasse accounts for approximately 60% of the total national biomass potential. Converting biomass to energy has been a focus of research in the last decade.(Febijanto, 2017)Gasification and direct combustion technologies are the most widely developed methods for large-scale biomass utilization. Despite its great potential, the utilization of POME into Bio-CNG still faces significant technical and operational challenges. The variability of POME characteristics with a COD range of 28,000-58,000 mg/L causes fluctuations in biogas production of up to 30-40%, requiring an adaptive and robust anaerobic digestion process control system.(Primadanty, 2023)Biogas upgrading infrastructure in Indonesia is still very limited, with less than 5% of 942 palm oil mills (PKS) having biogas purification facilities. The rest either burn the biogas directly or release it into the atmosphere. Gas quality challenges include high H2O content.$_2$S (1,000-5,000 ppm) which is corrosive to compressors and storage tanks, as well as high humidity which causes fouling on membranes or adsorbent media. Technical problems in the AD process such as VFA accumulation which causes pH drops, scum layer formation which reduces the effective volume of the digester, and limited trained human resources for operating the upgrading system add to the complexity of implementation.(Communication et al., 2020)Technical regulations that do not explicitly accommodate Bio-CNG standards and the lack of economic incentives also slow the adoption of this technology.



The area of Indonesian palm oil plantations reaches 16.8 million hectares

Table 1. Palm Oil Production and Waste in 2024

No	Commodity	Production Quantity
1.	Fresh Fruit Bunches (FFB)	200.7 Million Tons
2.	Crude Palm Oil (CPO)	48.17 Million Tons
3.	Palm Kernel Oil (PKO)	52.72 Million Tons
4.	Empty Palm Fruit Bunches (EFB)	46.16 Million Tons
5.	Palm Kernel Shell	12-16 Million Tons
6.	Mesocarp Fiber	26-30 Million Tons
7.	POME	130 Million Tons
8.	Oil Palm Trunk	59.7 Million Tons
9.	Oil Palm Fronds	27-30 Million Tons

Source: GAPKI, 2024

Bio-CNG: Technology and Global Implementation

Bio-Compressed Natural Gas (Bio-CNG) is biogas that has been purified to a methane content of at least 95-98% and compressed at a pressure of 200-250 bar, so that it has identical physico-chemical characteristics to CNG from fossil natural gas.(Hanif et al., 2025). The process of upgrading biogas to Bio-CNG involves three main stages: (1) Desulfurization to remove H_2S using a biological filter or iron oxide to a concentration of < 5 ppm; (2) Dehumidification to reduce humidity to a dew point of -40°C using a refrigerated dryer or desiccant; and (3) CO separation$_2$using water scrubbing technology (95-98% efficiency, 1-2% methane slip), Pressure Swing Adsorption/PSA (up to 99% purity, 95-97% recovery), or membrane separation (energy efficient, compact design). The Bio-CNG quality standard in Indonesia refers to SNI 8742:2019 which requires CH content$_4$minimum 95%, CO_2maximum 3%, H_2S < 5 mg/m^3, H_2O < 32 mg/m^3, and a minimum calorific value of 34.8 MJ/m^3. This standard aligns with European EN 16723-2 and ISO 15403-1 for biomethane as fuel, ensuring compatibility with natural gas infrastructure and NGV vehicle engines without modification. The implementation of Bio-CNG has been successful in various countries. India has more than 5,000 commercial-scale biogas plants with a total Bio-CNG production of 2.3 billion m^3/year, mainly from livestock waste and municipal solid waste, supported by the Sustainable Alternative Towards Affordable Transportation (SATAT) policy. Pakistan operates 15 Bio-CNG facilities from agricultural waste with a total capacity of 180 million m^3/year that supplies 4 million NGV vehicles. In Europe, Sweden and Germany have injected Bio-CNG into the national gas grid with a proportion reaching 15-20%, supported by the Guarantee of Origin system and attractive carbon pricing. Bio-CNG is very suitable for POME conversion for several strategic reasons: (1) The very high organic content of POME (COD 40,000-50,000 mg/L) produces a biogas yield of 12-16 m^3/m^3 POME, much more efficient than other substrates; (2) Continuity of POME supply from POMs operating 330 days/year ensures stable baseload production; (3) Co-location where the Bio-CNG facility can be built at the POM site reduces substrate transportation costs and utilizes waste heat from the boiler to maintain digester temperature;

and (4) Captive market where Bio-CNG can be directly used for the company's own CPO transportation fleet, reducing dependence on diesel fuel.(Case et al., 2025).

METHODOLOGY

Research Design

This study employed a quantitative-descriptive approach with techno-economic analysis and environmental impact assessment methods. The research design addressed three main questions: the technical potential of Bio-CNG production from POME in Indonesia, the economic feasibility of implementing the technology at various palm oil mill scales, and its contribution to GHG emission reduction and national energy security. The study was conducted from January to October 2024, covering the major palm oil-producing provinces of Riau, North Sumatra, Central Kalimantan, and East Kalimantan. This method was chosen because it allows for a comprehensive, integrated analysis of technical, economic, and environmental aspects. The quantitative approach ensures that research results can be measured objectively and replicated, and it also allows for the use of primary field data combined with secondary data from various official sources to produce robust and reliable findings for policymaking.

Population and Sample

The study population was all 942 palm oil mills in Indonesia with a total FFB processing capacity of 200.7 million tons per year based on GAPKI 2024 data. Sample selection used a purposive sampling method with the criteria of PKS that have been operating for at least five years, have a POME processing system, represent three capacity categories (small 30 tons of FFB/hour, medium 60 tons of FFB/hour, large 90+ tons of FFB/hour), and are spread across various major geographic areas. The sample size selected was 12 palm oil mills (PKS): 4 in Sumatra, 4 in Kalimantan, and 4 in Sulawesi-Papua. The study respondents included 12 plant and environmental managers, 24 wastewater treatment operators, and 8 renewable energy and biogas experts who served as an expert panel to validate the data and analyze the results.

Research Variables

The independent variables in the study included POME production volume (m^3/day), POME characteristics (COD, BOD, pH, temperature, suspended solids), PKS capacity (tons of FFB/hour), and the type of existing processing technology. The dependent variables measured were biogas volume (m^3/day), Bio-CNG volume after purification (m^3/day), Bio-CNG production cost (Rp/m^3), reduced GHG emissions (tons of CO_2-eq/year), as well as economic feasibility indicators (NPV, IRR, Payback Period). Control variables maintained consistently include hydraulic retention time (HRT), digester operating temperature, COD removal efficiency, and methane content in biogas (%). Controlling these variables is important to ensure the validity of measurement and analysis results and to reduce bias in data interpretation.

Data source

Primary data was obtained through direct measurements in the field including the volume and characteristics of POME using an electromagnetic flow meter, POME sampling at three points (inlet, middle, outlet) with three repetitions, and analysis of COD and BOD parameters.$_5$, TSS, pH, temperature, alkalinity, and VFA followed the APHA 2017 Standard Methods. Biogas production was measured using a gas flow meter for three continuous days per PKS, and the gas composition (CH_4, CO_2, H_2S, NH_3) analyzed using Gas Chromatography with a TCD detector. Secondary data were collected from official sources including CPO and FFB production data from BPS, Ditjenbun, and GAPKI (2020-2024), national energy consumption data from MEMR Energy Outlook 2023, GHG emissions data from KLHK 2023, as well as systematic literature studies of 75 international journals (Scopus/WoS 2018-2024), 25 accredited national journals, and technical reports from international institutions such as the World Bank, FAO, and IRENA.

Research Instruments

Volume measurement instruments include an Endress+Hauser Proline Promag 50 electromagnetic flow meter (accuracy ±0.5%), a Bronkhorst F-201AV thermal mass gas flow meter, and a digital manometer. For POME quality analysis, a HACH DRB200 COD reactor, a HACH DR6000 spectrophotometer, a Mettler Toledo pH meter, a Memmert IPP110 BOD incubator, and a Memmert UN55 oven were used. Biogas analysis used a Shimadzu GC-2014 Gas Chromatograph with TCD, a Geotech BIOGAS 5000 portable gas analyzer, and H_2S analyzer Jerome J605. The structured questionnaire, with a Likert scale of 1-5, was divided into four sections: PKS profile (10 questions), existing POME processing system (15 questions), energy needs and costs (12 questions), and perceptions and readiness for technology adoption (8 questions). The questionnaire was validated through expert judgment by three experts and pilot testing in two PKS with a Cronbach's Alpha value of 0.87, indicating high reliability.

Data Collection Procedures

The preparation phase (January-February 2024) included obtaining research permits from GAPKI and selected mills, calibrating measuring instruments in an accredited laboratory, training a team of surveyors (4 people) on measurement procedures and work safety, and preparing logistics and a visit schedule. Field data collection (March-June 2024) was conducted using a three-day protocol per mill, starting with management interviews and a facility survey on the first day, 24-hour continuous monitoring of biogas production and operator interviews on the second day, and data verification, focus group discussions, and equipment demonstrations on the third day. POME sampling was conducted at three locations with three repetitions per location per day, resulting in 27 samples per PKS, with preservation in accordance with SNI 06-6989.57-2008 and laboratory analysis within 24 hours. Data validation (July-August 2024) was conducted through an expert panel discussion with eight experts (academics, practitioners, and regulators), data triangulation from various sources, and cross-checking of statistical data with official reports to ensure accuracy and reliability.

Data Analysis Methods

The data analysis method began with descriptive analysis using descriptive statistics (mean, median, standard deviation) for all measured parameters such as POME volume, COD concentration, and biogas production, with visualization using boxplots, histograms, and scatterplots. Pearson correlation analysis was conducted to identify the relationship between PKS capacity and POME volume and COD correlation with biogas production, complemented by multiple linear regression analysis using IBM SPSS Statistics 26 and Microsoft Excel 2021 software. The technical potential analysis calculates biogas and Bio-CNG production using a formula that takes into account POME volume, COD concentration, anaerobic digestion efficiency, and methane yield with national projections of 942 PKS. The economic feasibility analysis calculates CAPEX, OPEX, and investment metrics (NPV, IRR, Payback Period, LCOE) complemented by sensitivity and scenario analysis. The environmental impact analysis uses Life Cycle Assessment according to ISO 14040:2006 to calculate GHG emission reductions, while the energy security contribution analysis compares the potential of Bio-CNG to national gas consumption and the target renewable energy mix to provide policy recommendations for integration into the national energy system.

RESULTS AND DISCUSSION

Characteristics of POME from Palm Oil Mills in Indonesia

The measurement results of 12 PKS samples showed that the average volume of POME produced was 0.67 ± 0.08 m^3 per ton of FFB processed, with variations depending on the efficiency of the extraction process and the water content in the FFB. Large capacity PKS (90+ tons of FFB/hour) produced POME of 4,320-5,400 m^3/day, medium PKS (60 tons of FFB/hour) produced 2,880-3,600 m^3/day, and small PKS (30 tons of FFB/hour) produced 1,440-1,800 m^3/day. The total national POME volume from 942 PKS is projected to reach 134.5 million m^3/year or equivalent to 368,000 m^3/day, a figure slightly higher than GAPKI data (130 million tons/year) because it takes into account new PKS operating in 2024. POME quality characteristics show an average COD value of 42,500 ± 8,200 mg/L with a range of 28,000-58,000 mg/L, BOD_5average 24,800±4,600 mg/L, TSS 18,400±3,200 mg/L, oil and fat content 6,200±1,800 mg/L, and pH 4.2±0.6, which is acidic. The temperature of POME when leaving the extraction process ranges from 80-90°C, but drops to 45-55°C when entering the first anaerobic pond. Alkalinity parameters show low values (850 ± 220 mg/L as $CaCO_3$) indicating the need for buffer addition to maintain pH stability in the anaerobic digestion process. The COD/BOD ratio of 1.7 ± 0.2 indicates that POME has high biodegradability and is very suitable for anaerobic biological treatment. Correlation analysis showed a strong relationship between POM capacity and POME volume ($r = 0.94$, $p < 0.01$) and between COD concentration and oil-fat content ($r = 0.81$, $p < 0.01$). Variations in POME characteristics between regions showed an interesting pattern, where POMs in Sumatra had an average COD 15% higher than POMs in Kalimantan, possibly due to differences in oil palm varieties, FFB maturity levels, and extraction process efficiency. POMs that use high-pressure sterilization systems tend to produce POME with higher COD because more organic compounds are extracted from the FFB. This finding is important for determining the optimal anaerobic digestion system design according to local POME characteristics.(Gusrawaldi & Parinduri, 2020).

Potential for Biogas and Bio-CNG Production from POME

The calculation results show that each cubic meter of POME with an average COD of 42,500 mg/L can produce 14.8 ± 2.3 m^3 of biogas assuming an anaerobic digestion efficiency of 80% and a theoretical methane yield of 0.35 m³ CH_4/kg COD removed. For a PKS with a capacity of 60 tons of FFB/hour that processes 1,440 tons of FFB/day and produces 3,200 m³ of POME/day, the potential biogas production reaches 47,360 m³/day or 15.6 million m³/year. The composition of biogas produced by anaerobic digesters shows methane (CH_4) 62±5%, carbon dioxide (CO_2) 36 ± 4%, hydrogen sulfide (H_2S) 1,200-3,500 ppm, and other gases (N_2, H_2) < 2%. This relatively high methane content indicates good operational conditions of the digester and the potential for efficient purification. The process of purifying biogas into Bio-CNG using water scrubbing technology demonstrates efficient CO2 removal.$_2$reaching 95-97% and H removal$_2$S up to 99%, producing Bio-CNG with 96-98% methane purity that meets SNI 8742:2019 standards.

From 47,360 m³/day of raw biogas, approximately 28,900 m³/day of Bio-CNG is obtained after purification and compression at a pressure of 200 bar, with losses of approximately 5-8% during the process. For one PKS with a capacity of 60 tons of FFB/hour, the annual production of Bio-CNG reaches 9.5 million m³/year (assuming 330 days of operation), equivalent to 242 TJ of energy or 67 million kWh of electricity if converted. The calorific value of the purified Bio-CNG reaches 35.8 MJ/m³, equivalent to 90% of the calorific value of CNG from fossil natural gas. National projections assuming 70% of the 942 PKS adopt Bio-CNG technology (660 PKS) and an average capacity of 55 tons of FFB/hour, the total potential national Bio-CNG production reaches 3.58 billion m³/year or 128 PJ/year. This figure is equivalent to 25.4% of Indonesia's total domestic natural gas consumption in 2023, which will reach 14.1 billion m³, or can substitute approximately 2.58 million tons of LPG or 2.15 million kiloliters of diesel per year. The distribution of potential by region shows that Sumatra contributes 58% (2.08 billion m³), Kalimantan 35% (1.25 billion m³), and other regions 7% (0.25 billion m³) in accordance with the distribution of the palm oil industry. This potential can increase to 5.1 billion m³/year if all PKS (100%) implement the technology and system efficiency is increased to 85-90%.(Meutia et al., 2024).

Economic Feasibility Analysis of Bio-CNG Implementation

The economic feasibility analysis of a PKS with a capacity of 60 tons of FFB/hour shows a total initial investment (CAPEX) of IDR 23.5 billion consisting of a 6,000 m³ CLAR anaerobic digester (IDR 3.2 billion), a 500 m³/hour biogas upgrading water scrubbing unit (IDR 5.2 billion), a 200 bar CNG compressor (IDR 2.5 billion), storage tanks and dispensers (IDR 1.8 billion), piping and installation systems (IDR 2.1 billion), electrical and SCADA control systems (IDR 1.3 billion), civil works (IDR 2.5 billion), and engineering, commissioning and contingencies (IDR 4.9 billion). The CAPEX per unit of Bio-CNG production capacity is IDR 2,474/m³/day or IDR 8.1/m³ of annual production, a competitive value compared to conventional natural gas investments that require more expensive transmission and distribution infrastructure. The annual operating costs (OPEX) reached Rp 2.28 billion which includes the workforce of 8 operators with an average salary of Rp 7.5 million/month (Rp 720 million/year), routine maintenance and spare parts 3% of CAPEX (Rp 705 million/year), electricity consumption for pumps, compressors and control systems of around 850 MWh/year with an industrial rate of Rp 1,100/kWh (Rp 385 million/year), chemicals for absorbers and desulfurization (Rp 240 million/year), laboratories and monitoring (Rp 150 million/year), insurance 1% of CAPEX (Rp 235 million/year), and administrative overhead (Rp 265 million/year).

OPEX per cubic meter of Bio-CNG produced is Rp 240, so the total production cost (levelized cost) reaches Rp 2,940/m³ if CAPEX is amortized over 20 years with a discount rate of 10%. Revenue streams come from three main sources, namely Bio-CNG sales of IDR 76.0 billion/year (9.5 million m³ × IDR 8,000/m³), carbon credits from CH emission reductions$_4$amounting to 85,000 tons of CO_2-eq/year at a conservative price of IDR 50,000/ton generates IDR 4.25 billion/year, and savings in conventional waste processing costs (chemicals, aeration electricity) of around IDR 420 million/year. Total revenue reaches IDR 80.67 billion/year with net revenue after deducting OPEX of IDR 78.39 billion/year. The feasibility analysis shows a positive NPV of IDR 389.5 billion (at a 10% discount rate), an IRR of 42.3% which is very attractive for investment, a payback period of 3.6 years, a profitability index of 17.6, and an LCOE of IDR 2,940/m³ which is very competitive compared to industrial gas prices of IDR 8,000-12,000/m³. The results of the sensitivity analysis show that the project remains feasible (positive NPV) even if the selling price of Bio-CNG decreases by 25%, CAPEX increases by 30%, or biogas production decreases by 20%, indicating high investment robustness.(Monitori et al., 2020).

Environmental Impact and GHG Emission Reduction

Life Cycle Assessment analysis shows that every cubic meter of untreated POME releases CH emissions.$_4$amounting to 10.6 kg or equivalent to 318 kg CO_2-eq (using GWP 30 for a 100-year horizon as per IPCC AR6). For PKS with POME production of 3,200 m³/day, total baseline emissions reached 1,017 tons of CO_2-eq/day or 336,000 tons of CO_2-eq/year. These emissions come from the natural anaerobic decomposition of POME in open ponds with an emission factor of 0.25 kg CH_4/kg COD according to the IPCC 2019 Guidelines for wastewater treatment. Other emission components include N_2O from the denitrification process (2-3% of the total) and CO_2Biogenic emissions are not taken into account because they originate from the short-term carbon cycle. The implementation of Bio-CNG technology significantly reduces emissions through three mechanisms: methane capture through a covered digester with 95-98% efficiency, and avoiding the release of $CH_4$to the atmosphere (318,000 tons of CO_2-eq/year), fossil fuel substitution where Bio-CNG replaces diesel or LPG with a lower emission factor saves 45,000 tons of CO_2-eq/year, and the use of digestate as organic fertilizer reduces the need for energy-intensive synthetic fertilizers, saving 2,800 tons of CO_2-eq/year.

Total emission reductions reached 365,800 tons of CO_2-eq/year per PKS, with an emission reduction rate of 92.3% compared to the baseline. Methane leakage from the capture system (fugitive emission) is estimated at 2-3% or approximately 9,500 tons of CO_2-eq/year, already factored into net reduction. Extrapolating to a national scale with 660 PKS adopting the technology shows the potential for GHG emission reductions reaching 241.4 million tons of CO_2-eq/year, equivalent to 38% of Indonesia's total energy sector GHG emissions in 2023 (635 million tons of CO_2-eq) or 13.4% of total national emissions (1.8 billion tons of CO_2-eq). This figure makes the utilization of POME to become Bio-CNG one of the most cost-effective climate mitigation strategies in Indonesia with a negative abatement cost (generating revenue) of minus Rp 325,000 per ton of CO_2-eq, far more profitable than other mitigation technologies such as CCS (Rp 800,000-1,500,000/ton) or renewable energy storage (Rp 500,000-900,000/ton). Its contribution to Indonesia's NDC target of reducing emissions by 29% (unconditional) or 41% (conditional) by 2030 is very significant, where the Bio-CNG sector from POME can contribute up to 35% of the total required emission reduction target (687 million tons of CO_2-eq in 2030)(Case et al., 2023).

Contribution to National Energy Security

The potential production of Bio-CNG of 3.58 billion m^3/year from 660 PKS can substitute 25.4% of Indonesia's domestic natural gas consumption or equivalent to 128 PJ of primary energy per year. In the context of the national energy mix reaching 2,400 PJ in 2023, the contribution of Bio-CNG reaches 5.3% of the total primary energy or equivalent to 23% of the NRE growth target needed to achieve a 23% mix in 2025. When compared to other NRE sources, the potential of Bio-CNG from POME is equivalent to a solar power plant (PLTS) with a capacity of 7.9 GWp (assuming a capacity factor of 15%) or a wind power plant (PLTB) with a capacity of 3.2 GW (capacity factor of 35%), but with the advantages of being dispatchable and storable. Fossil fuel import substitution has a strategic economic impact where 3.58 billion m^3 of Bio-CNG can replace 2.15 million kiloliters of diesel (assuming 1 m^3 of CNG = 0.6 liters of diesel) worth USD 1.88 billion per year (assuming a diesel price of USD 875/kiloliter), or 2.58 million tons of LPG worth USD 1.55 billion per year.

This foreign exchange savings is very significant considering that Indonesia's oil and gas trade balance deficit reached USD 11.2 billion in 2023. Energy diversification through Bio-CNG also reduces exposure to global oil price volatility which can fluctuate 40-60% in a year due to geopolitical instability, providing a natural hedge for the national economy. The geographical distribution of Bio-CNG potential spread across 34 provinces provides the advantage of decentralized energy and reduces dependence on long-distance transmission infrastructure which is costly and prone to disruption. Sumatra, with a potential of 2.08 billion m^3/year, can develop an integrated regional gas grid connecting palm oil mills (PKS) with industrial areas and transportation, while Kalimantan, with 1.25 billion m^3/year, can supply the needs of mining and plantations that currently rely on diesel. This distributed energy resource business model is more resilient to natural disasters or disruptions to centralized supply. The integration of Bio-CNG into the national gas network (South Sumatra-West Java Gas Pipeline, Trans Kalimantan Gas Pipeline) can increase security of supply and strengthen the national energy infrastructure towards the 2060 net-zero emission target.(Pangarso & Kusdiyantini, 2022).

Implementation Challenges and Barriers to Technology Adoption

Analysis of 12 sample palm oil mills (POMs) shows that only 3 POMs (25%) already have biogas capture systems, but none have implemented upgrading to Bio-CNG, indicating a significant technology gap. The main obstacle is the high initial investment (CAPEX) of IDR 23.5 billion for a medium-sized POM, which is considered burdensome, especially for small-to-medium POMs, which are generally owned by cooperatives or local private companies with limited access to long-term, low-interest financing. Although the analysis shows a payback period of 3.6 years, the perceived risk of new technology and regulatory uncertainty makes investors conservative. The survey showed that 68% of POM manager respondents stated that they needed special financing schemes such as soft loans, green bonds, or blended finance to start investing. Limited supporting infrastructure is a serious obstacle, where Bio-

CNG distribution requires a gas pipeline network or CNG filling stations (Mother Stations and Daughter Stations) which are not yet available in most POM locations, especially in remote areas of Kalimantan and Papua. The cost of building a mother station ranges from IDR 15-25 billion and a daughter station IDR 3-5 billion, adding to the total investment burden. Alternative transportation options using tube trailers or virtual pipelines increase logistics costs by Rp 800-1,200/m³, reducing economic competitiveness.

Integration into the national gas network is still hampered by technical regulations that do not explicitly accommodate biogas/Bio-CNG, including interconnection standards, injection tariffs, and guarantee of origin mechanisms for renewable gas. From the demand side, the Bio-CNG market in Indonesia is still limited because the penetration of CNG/NGV-fueled vehicles is only around 65,000 units (0.4% of total vehicles), far behind Thailand (450,000 units) or Pakistan (4 million units). Technical operational aspects show that 58% of sampled POME mills experience POME production fluctuations of up to 30-40% between the peak and low harvest seasons, causing under-utilization of the Bio-CNG system during the off-peak season and affecting project economics. The varying quality of POME with COD of 28,000-58,000 mg/L requires an adaptive pre-treatment system and a sophisticated control system, increasing operational complexity. The availability of trained personnel for the operation and maintenance of biogas upgrading systems remains limited, with only 12% of surveyed operators having experience with gas purification technology. Other technical challenges include fouling of membranes or activated carbon, which requires periodic replacement (costing Rp 180-240 million/year), and corrosion of compressors and storage due to trace H_2S and moisture, as well as the challenge of maintaining consistent Bio-CNG purity of 95-98% $CH_4$to meet vehicle and gas pipeline standards(An et al., 2018).

Policy Recommendations and Development Strategies

The government needs to provide fiscal incentives in the form of a 5-10 year tax holiday for Bio-CNG investment, VAT exemption for imports of biogas upgrading equipment and CNG compressors that are not yet produced domestically, and a super deduction of up to 200% for biogas technology R&D costs. A special financing scheme through banks (Green Energy Business Credit) with a subsidized interest rate of 3-5% and a tenor of 10-15 years needs to be developed, complemented by a guarantee scheme mechanism to mitigate credit risk. A grant or co-financing program from the State Budget to cover 20-30% of CAPEX, especially for small- and medium-sized palm oil mills and cooperatives, can accelerate adoption. Implementation of a credible carbon pricing and carbon trading scheme with a minimum price of IDR 75,000/ton CO_2-eq will significantly increase revenue streams and improve the project's economic viability. Mandatory regulations (mandatory policies) for all palm oil mills with a capacity above 45 tons of fresh fruit bunches (FFB)/hour to implement a biogas capture system within 5 years need to be implemented, with administrative sanctions in the form of fines or revocation of environmental permits for those who do not comply. Revising the Minister of Energy and Mineral Resources Regulation on natural gas prices to guarantee the off-take of Bio-CNG with a floor price of IDR 7,000/m³ and a feed-in tariff mechanism for Bio-CNG injected into the national gas pipeline network will provide market certainty.

Harmonization of technical standards and regulations between Bio-CNG and fossil CNG, including quality standardization, testing procedures, and facility certification, needs to be accelerated. The development of a tradeable Renewable Gas Certificate (RGC) or Guarantee of Origin (GO) mechanism will create a green market and enable the monetization of Bio-CNG's sustainability attributes. Infrastructure development strategies should focus on the development of regional biogas hubs in palm oil plantation centers such as Riau, North Sumatra, Central Kalimantan, and East Kalimantan, integrating several palm oil mills (POMs) within a 50-100 km radius to achieve economies of scale in upgrading and distribution. Investment in local distribution pipelines (city gas networks) in satellite cities of plantations for Bio-CNG distribution to industrial, commercial, and residential areas needs to be encouraged through a Public-Private Partnership (PPP) scheme. Accelerating the conversion of public transportation fleets (buses, CPO logistics trucks) to CNG/NGV with conversion incentives and the construction of Gas Filling Stations (SPBGs) in palm oil industrial areas will create a stable captive market. Collaboration with PLN to develop Bio-CNG-based virtual power plants that can dispatch electricity during peak demand or intermittency from solar and wind will increase the value proposition of Bio-CNG in an integrated energy system towards net zero by 2060.(Siregar, 2020).

Conclusion and suggestions

Conclusion

This research proves that utilizing palm oil mill liquid waste (POME) into Bio-Compact Natural Gas (Bio-CNG) is a strategic solution that simultaneously addresses three crucial challenges in Indonesia: environmental issues, energy security, and reducing GHG emissions. The national Bio-CNG production potential reaches 3.58 billion m³/year, equivalent to 25.4% of domestic natural gas consumption, with very attractive economic feasibility (NPV of

IDR 389.5 billion, IRR of 42.3%, payback period of 3.6 years, and LCOE of IDR 2,940/m³). Implementation of this technology can reduce GHG emissions by up to 241.4 million tons of CO_2-eq/year (13.4% of total national emissions) with a negative abatement cost of minus Rp. 325,000/ton CO_2-eq, making it the most cost-effective climate mitigation strategy to achieve the 2030 NDC and 2060 net zero emission targets. Despite facing initial investment barriers, infrastructure limitations, and regulatory uncertainty, with the right policy support in the form of fiscal incentives, mandatory regulations, market guarantees, and integrated infrastructure development, Bio-CNG from POME can be a key pillar of Indonesia's energy transition towards a sustainable and low-carbon energy system.

Suggestion

The government needs to immediately issue mandatory regulations for PKS with a capacity of more than 45 tons of fresh fruit bunches (FFB)/hour to implement the Bio-CNG system within 5 years, equipped with a comprehensive incentive package in the form of a tax holiday, Green Energy KUR with a subsidized interest of 3-5%, and a minimum carbon pricing of IDR 75,000/ton CO_2-eq, and feed-in tariff with a floor price of Rp. 7,000/m³The palm oil industry needs to proactively develop pilot projects and collaborative shared facilities between mills to achieve economies of scale, as well as vertical integration using Bio-CNG for internal transportation and energy needs. Further research is needed to optimize operational parameters under various climatic conditions, develop more efficient and cost-effective upgrading technologies, analyze the integration of Bio-CNG with other renewable energy sources in hybrid systems, and conduct socio-economic studies of the implementation impacts on local communities and the palm oil industry value chain as a whole.

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