

Economic Assessment of Bio-DME Production from Oil Palm Empty Fruit Bunches: Decarbonizing Diesel-Heavy Mining Operations in Kalimantan, Indonesia

Rudy Heryadi^{1*}, Ulpen Hiermy², Adiman², Siti Ramdiah³, Fujianor Maulana¹, Difo Miftahul Faridl¹, Hendera¹, M Saufi⁴

¹Department of Environmental Science, PGRI Kalimantan University, Banjarmasin 70122, Indonesia

²Mechanical Engineering Department, Bina Tunggal College of Technology, Bekasi 17132, Indonesia

³Department of Biology Education, PGRI Kalimantan University, Banjarmasin 70122, Indonesia

⁴Department of Information Technology, PGRI Kalimantan University, Banjarmasin 70122, Indonesia

*Corresponding author's email: rudy.heryadi@breny.my.id

Article info:

Received: 8 January 2026

Revised: 15 July 2026

Accepted: 10 August 2026

DOI:

[10.69650/rast.2026.265616](https://doi.org/10.69650/rast.2026.265616)

Keywords:

Diesel

DME

Economic

Feasibility

OPEFB

ABSTRACT

Biomass from Oil Palm Empty Fruit Bunches (OPEFB) is a potential renewable energy source in Indonesia that can be efficiently converted into fuel products, such as DME. Although research exists on DME production using OPEFB, no significant economic assessment or feasibility study of OPEFB-based bio-DME plants replacing diesel fuel is currently underway. This research assesses the feasibility of an OPEFB-based bio-DME plant as a diesel replacement. The method determines the potential of OPEFB raw material, estimates investment and operating costs, and evaluates economic feasibility parameters. Based on the economic evaluation, the net present value (NPV) and internal rate of return (IRR) are USD 92.99 million and 17%, respectively, for a 30-year plant life and an investment of USD 180.93 million. Only 6.25% of the OPEFB-based bio-DME produced can substitute for the non-subsidy diesel consumption of a nearby coal mine, while savings obtained by substituting diesel amount to USD 18.55 million per year. Plant capacity and capital expenditure (CAPEX) are most sensitive to disturbances, requiring capacity utilization above 74% and CAPEX increases below 38.3% to remain viable, whereas the OPEFB feed price is least sensitive. Additionally, substituting fossil diesel yields a highly favorable estimated carbon abatement cost of USD -617 per tonne of CO₂ avoided. This research confirms that OPEFB-based bio-DME should be viewed not merely as a waste-management strategy but as a critical component of Indonesia's energy transition.

1. Introduction

Renewable energy is a necessity in Indonesia. Among the various renewable energy alternatives available, biomass has considerable potential for development in Indonesia. The biomass potential in Indonesia is approximately 32 GWe, and recent utilisation was only around 1,740.40 GWe, or 5.4% of the total potential [1]. This significant underutilization highlights a critical opportunity within the national energy matrix. As a tropical archipelago situated on the equator, Indonesia has a distinct advantage in biomass productivity compared to temperate regions, enabling year-round continuous feedstock harvesting. Unlike intermittent renewable sources such as solar or wind, which require expensive storage solutions to ensure grid stability, biomass offers baseload power capabilities and the versatility to be converted into solid, liquid, or gaseous fuels. Consequently, accelerating the deployment of bioenergy technologies is not merely a matter of meeting international climate commitments but a strategic imperative to enhance energy security. By diversifying the energy mix away from finite fossil reserves, Indonesia can foster sustainable regional economic development, creating a resilient energy infrastructure that supports industrial growth while mitigating the environmental impacts of traditional carbon-intensive power generation.

Biomass can be utilised as an energy source through gasification. Gasification is a thermochemical process that converts biomass into a gas called producer gas or synthetic gas (syngas). Syngas is a fuel-

based mixture consisting mainly of Hydrogen (H₂), Carbon Monoxide (CO), and Methane (CH₄) [2, 3]. Syngas is a raw material for many other chemical products, including methanol, ammonia, and Dimethyl Ether (DME). One of the biomass sources with significant potential for utilisation is oil palm empty fruit bunch (OPEFB) waste. Indonesia is currently the world's largest producer of palm oil, and, in line with this, the waste generated is also substantial, including OPEFB [4, 5].

Abundant OPEFB resources have the potential to serve as raw materials for further chemical synthesis via gasification. Bio-DME produced from OPEFB waste is 4% of the total palm oil waste produced, while the other palm oil waste produced consists of solid and liquid waste [6]. Despite the promise of OPEFB as a feedstock, its utilization has historically been limited to low-efficiency applications, such as mulching or direct combustion in boilers, which often pose environmental issues due to particulate emissions. Upgrading OPEFB to a high-value liquid or gaseous fuel, such as DME, represents a significant leap in the value chain. Unlike Methanol, which requires significant engine modifications, or Hydrogen, which faces infrastructure hurdles, DME offers a middle-ground solution. It utilizes known gasification and DME synthesis technologies. It can be deployed in diesel engines with modifications primarily to the fuel injection system, making it a pragmatic transitional fuel for heavy industry.

The percentage and type of palm oil waste produced are shown in the following Figure 1, which is processed from source [6].

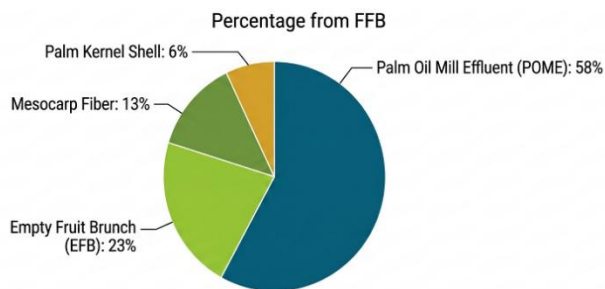


Fig. 1 Percentage of oil palm waste.

OPEFB is often converted into biofuel via the gasification process, in which the biomass undergoes several reaction steps to produce the end product. This thermochemical process converts biomass into a syngas [3, 7]. Syngas can be further processed into DME, which can then be used as a diesel fuel substitute. DME has a higher cetane number than regular diesel fuel and self-ignition characteristics that make it suitable for use as a diesel engine fuel, with some modifications to the fuel distribution system, since DME is a gas at room temperature [8, 9]. Table 1 presents the properties of DME and diesel [9].

Table 1 DME and diesel properties.

Property	DME	Diesel
Chemical formula	CH_3OCH_3	$\text{C}_8 - \text{C}_{25}$
Molecular weight	46.07	96 and greater
Vapour pressure at 20 °C (bar)	5.1	<0.01
Boiling point (°C)	-25	150-380
Liquid density at 20 °C (kg/m^3)	660	800-840
Liquid viscosity at 25 °C (kg/ms)	0.12-0.15	2 – 4
Gas specific gravity (versus air)	1.59	-
LHV (MJ/kg)	28.43	42.5
Cetane number	55 - 60	40 – 55
Stoichiometry air-to-fuel ratio (kg/kg)	9	14.6

The urgency of the transition from diesel to DME is particularly acute in Indonesia's industrial sectors, specifically mining. Mining operations in remote areas, such as Kalimantan, are heavily reliant on diesel fuel not only for heavy machinery (excavators, dump trucks) but also for stationary power generation in off-grid locations. The logistics of transporting fossil diesel to these remote sites incur high costs and a large carbon footprint. Consequently, the concept of localized energy production, where fuel is generated near the point of consumption from local biomass, offers dual advantages: it mitigates the volatility of global fossil fuel prices. It reduces the logistical overhead of fuel supply chains. Research on DME as a substitute for conventional fuels has expanded significantly in recent years. The existing literature generally falls into three distinct thematic strands: combustion and engine performance, environmental life-cycle assessments (LCA), and techno-economic or logistical feasibility [10–14].

Within the context of combustion and performance, studies have extensively documented DME's viability as a mechanical substitute for diesel. Park et al. [12] reviewed the applicability of DME in heavy-duty engines, demonstrating its superiority in minimizing soot production and reducing ignition delay due to its high cetane number, while noting technical shortcomings such as its low heating value and poor lubricity. To address these specific mechanical limitations,

Makos et al. [15] investigated fuel formulation strategies, concluding that blending DME with regular diesel, biodiesel, or liquefied petroleum gas (LPG) can sufficiently improve lubricity and viscosity, resulting in better overall engine performance than conventional diesel alone.

From an environmental perspective, life-cycle assessment (LCA) has demonstrated the potential to reduce greenhouse gas (GHG) emissions from biomass-derived DME. Lecksiwilai et al. [16] analysed the net energy ratio (NER) and GHG life-cycle emissions of DME produced from various agricultural wastes in Thailand, including OPEFB. While their results indicated that OPEFB has the second-lowest NER value and the second-highest GHG emissions among the tested residues, they also highlighted the need to optimize waste heat utilization during production. However, their study focused strictly on environmental metrics and lacked a specific techno-economic analysis.

Regarding techno-economic and logistical feasibility, prior work has shown that localized DME production can economically replace diesel consumption at remote sites. However, these studies rely on vastly different feedstocks or geographic parameters. McFarlan [13] examined the techno-economic feasibility of using methanol and DME to replace diesel in off-grid, remote areas of Northern Canada, demonstrating that localized DME synthesis is highly cost-competitive against the logistical premium of transporting fossil diesel. Similarly, Tunå & Hulteberg [14] conducted a comparative techno-economic study of various biofuels, concluding that DME derived from woody biomass exhibits the highest efficiency and lowest cost per 100 km when used in heavy-duty diesel engines.

As summarised in Table 2, while these distinct strands of literature thoroughly explore DME's mechanical viability, environmental profile, and general economics, a critical intersection remains largely unaddressed. Specifically, there are a few significant studies evaluating OPEFB-based bio-DME as a heavy-duty diesel substitute. To date, the few existing techno-economic models focusing directly on OPEFB [4, 17] have exclusively evaluated DME as a substitute for domestic LPG for cooking. No dedicated techno-economic assessment has yet bridged the gap to evaluate OPEFB-based bio-DME for diesel replacement in the highly localized, off-grid context of the mining sector. The utilisation of OPEFB as a feedstock for DME production, serving as a diesel substitute, can also be further implemented in other countries with significant palm oil plantations in tropical regions.

The OPEFB-based bio-DME plant selected for the study is located in Tamiang Layang, East Barito Regency. This study utilised OPEFB potential data from palm oil mills located in East Barito Regency, Central Kalimantan Province, and its surrounding areas. The location selection was based on the Central Kalimantan government's plan to develop East Barito as a special economic zone [18].

While existing techno-economic assessments have extensively modeled alternative fuels, this study advances beyond the current literature through two specific novel contributions. First, regarding feedstock, whereas most DME models rely on coal or idealized woody biomass, this study uses OPEFB. This highly abundant, yet complex and high-moisture, agricultural residue demonstrates economic viability without blending. Second, regarding the target end-use, rather than evaluating DME as an LPG substitute for domestic cooking or light-duty urban transport, this research exclusively evaluates DME as a heavy-duty diesel substitute for remote mining operations, capturing the severe logistical premiums paid for fossil fuels in remote regions.

Table 2 Summary of studies of DME as diesel substitutes.

Author (s)	Raw material for DME production	DME Utilisation as a Diesel Substitute
Makos et al. [15]	No information	The study focuses on the potential of DME as an environmentally friendly vehicle fuel. In this article, the DME can be used as a Diesel fuel substitute to reduce the environmental burden.
Lecksiwilai et al. [16]	OPEFB, Cassava rhizome, rice straw, sugar cane tops and leaves, maize stem	A study on the life cycle greenhouse gas emissions of DME from agricultural waste. The study focuses more on which type of agricultural waste is best for reducing life-cycle GHG emissions. There is no discussion on the application of DME as a replacement for diesel fuel.
McFarlan [13]	No information	A Techno-Economic Analysis (TEA) on DME and Methanol as a Diesel substitute for power generation in remote regions in Northern Canada (Nunavut region). The TEA study emphasises logistics and transportation, where DME and methanol are viable alternatives.
Tunå & Hulteberg [14]	Woody biomass	This study demonstrates that DME, as a diesel fuel substitute, is feasible compared to other renewable biofuels. In terms of fuel cost and efficiency, DME is superior when used as a Diesel substitute. This study presents an economic assessment, but no specific biomass feedstock is mentioned.
Park et al. [9]	No Information	A review study that summarises the application of DME as a substitute for diesel fuel. The DME exhibits superiority in various aspects, including a high cetane number that shortens ignition delay, minimal soot production, and a nearly zero contribution to greenhouse gas emissions. There is no discussion about its economic feasibility.

2. Method

There are six main steps in this study: (1) determination of OPEFB and production scenario, (2) material balance of OPEFB-based DME production, (3) economic analysis, (4) Diesel budget saving analysis, (5) sensitivity analysis, and (6) indicative carbon abatement cost analysis.

2.1 Determination of OPEFB feedstock potential and production scenario

The DME production facility was assumed to be built in Tamiang Layang, Dusun Timur district, East Barito, Central Kalimantan. Tamiang Layang has a strategic location as one of the main routes from Central Kalimantan and West Kalimantan to the new capital, Nusantara. Figure 2 shows the location of Tamiang Layang in Kalimantan.

The DME production facility in East Barito is assumed to produce OPEFB-based bio-DME as a diesel substitute for a nearby coal mining company, PT Adaro Andalan Indonesia Tbk [19]. The distance from the plant location to the mining area is approximately 50-75 km. In Indonesia, particularly in Kalimantan, numerous mining companies operate, with coal mining companies being the most dominant. The mining operation's diesel costs account for 30% to 35% of its total operational costs [20], and its diesel consumption exceeds that of other sectors in Kalimantan, where the transportation sector consumes around 990,000 tonnes per year [21]. PT Adaro Andalan Indonesia Tbk, a coal mining company, consumes approximately 550,000 kiloliters of diesel or 666,667 tonnes annually [22].

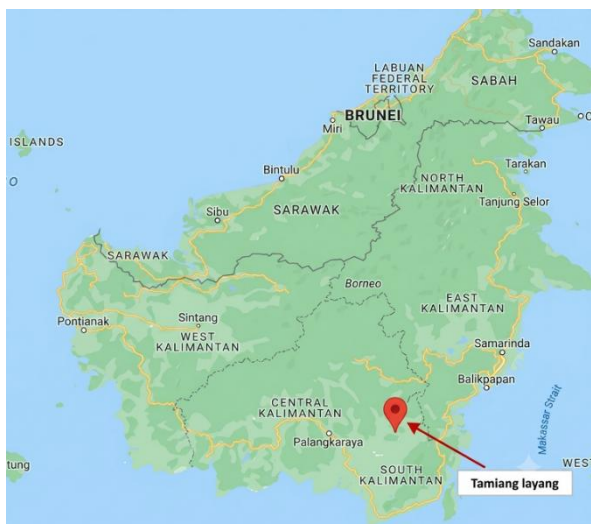


Fig. 2 Tamiang Layang location (Map data: Google, ©2022)

The collection area of OPEFB was set at a 100 km radius from the proposed DME plant location in Tamiang Layang. There are 5 Palm Oil Mills (POM) within a 100 km radius of Tamiang Layang. There are two POMs with a 60 tonnes/hour fresh fruit bunch (FFB) production capacity and 1 POM with a 45 tonnes/hour FFB. Also, there are two POMs with a 30 tonnes/hour rate. POM typically runs 24 hours a day, 7 days a week, for 328.5 days [23]. OPEFB feed composition based on proximate analysis has 60% water content, 1.46% ash content, 34.84% volatile matter, and 3.71% fixed carbon [24]. OPEFB feedstock potential was obtained from an earlier study by Heryadi et al. [4].

This study explicitly employs a process simulation approach, using established research databases rather than direct pilot-plant data. The current lack of commercial-scale OPEFB-to-DME facilities in the East Barito region and its vicinity necessitates this choice. Furthermore, to account for the specific properties of OPEFB, particularly its high moisture and alkali content, the process model includes drying costs and sufficient maintenance costs for fouling resulting from the gasification process.

2.2 Material balance of OPEFB-based bio-DME production

Aspen HYSYS process simulation software was used to simulate a single-stage DME synthesis using syngas derived from the gasification process, fed to the DME synthesis reactor and then to the purification process. This process simulation aids in determining the material and energy flow. The OPEFB-based bio-DME production process explanation was based on a process flow diagram (PFD) shown in Figure 3.

The DME plant with a capacity of 41 tonnes/hour OPEFB was modeled in this study. OPEFB collected and transported to the DME plant was assumed to have 60 wt% moisture content and 1.46 wt% ash [24]. The OPEFB feedstock rate for simulation was converted into a dry ash-free (daf) basis; therefore, the feedstock rate becomes 16 tonnes/hour. The process configuration used for simulation purposes of DME production was adopted from several previous studies [25–28] and carried out using Aspen HYSYS, including an OPEFB-based bio-DME production simulation parametric study by Inayat et al. [29]. Because the OPEFB raw material is not a standard component in Aspen HYSYS, it must be entered manually as a hypothetical solid component. Based on the ultimate analysis, the OPEFB was entered as a hypothetical solid component. The basis for the simulation is dry ash-free (daf), and the chemical formula of OPEFB as an input in Aspen HYSYS was $C_{4.306}H_{6.176}O_{2.587}N_{0.048}S_{0.003}$ [30]. The DME plant design was conducted in the following steps.

OPEFB pretreatment

Raw OPEFB with a high moisture content underwent drying. Excess steam generated and off-gas boiler hot flue gas from the production of OPEFB-based bio-DME can be utilised to fulfil the thermal energy required for drying.

Gasification

The gasification process occurs in a fluidized-bed gasifier, and the process flow, assumptions, and parameters are used as in a previous study by Heryadi et al. [3]. As an oxidant, the gasifier uses steam and oxygen. The cryogenic air-separation process produced oxygen. The oxygen purity was assumed to be 100%. The syngas composition from gasification was calculated using an equilibrium reaction at 900 °C. During the gasification reaction, the process was assumed to be isothermal [31]. The waste heat from the gasifier was used to generate steam (steam generator I). The generated steam is intended for supply to the distillation columns.

Water-gas shift

The water-gas shift (WGS) reaction adjusts the H_2/CO ratio to 1 [32]. The reaction temperature is at 400 °C, and the pressure is 1,000 kPa [33]. Before the acid gas removal process, the syngas is cooled to 25 °C [27]. The WGS type used is high-temperature WGS, which favors the WGS reaction and yields a higher reaction rate [33].

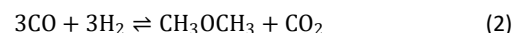
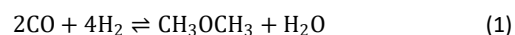
Water removal and syngas cleaning

Water removal was modeled using a separator as a dryer, and acid gas removal was modeled using a component splitter. The removal process was modeled using a water separator, which removes water with a concentration below 1% mol as an acceptable level [33].

After removing the water, the syngas enters the acid removal, modeled as a component splitter. CO_2 and H_2S removal rates were assumed to be 90% and 100% [33,34].

DME Synthesis

Purified syngas is compressed to 5,000 kPa, corresponding to the JFK process's operating pressure. The Gibbs reactor simulates the synthesis of DME, and the reaction involved is an equilibrium reaction [35]. The reactor's operating temperature is based on the JFK process at 260 °C [36]. The temperature was maintained at 260 °C throughout the reaction. Reactions of single-stage DME synthesis are shown in (1) and (2) [37].



Distillation

The first tower's distillation process primarily separated CO_2 and other light gases from DME, methanol, and water (off-gas tower). The tower has 11 stages, with the feed stage located on stage number 3 from the condenser at the top. The gas, as a top product, is mixed with the outlet gas from the Gas-Liquid separator and sent to the steam boiler as fuel. As it enters the DME Tower, DME, methanol, and water are in the bottom product. Distillation in the DME tower separates DME as the top product from methanol and water as the bottom products. The DME tower has six stages, and the feed stage is located on stage number 2 from the top. The bottom products from the DME Tower, methanol and water, were further separated in the methanol tower. The top product of the distillation in the methanol tower was methanol, and the bottom was water.

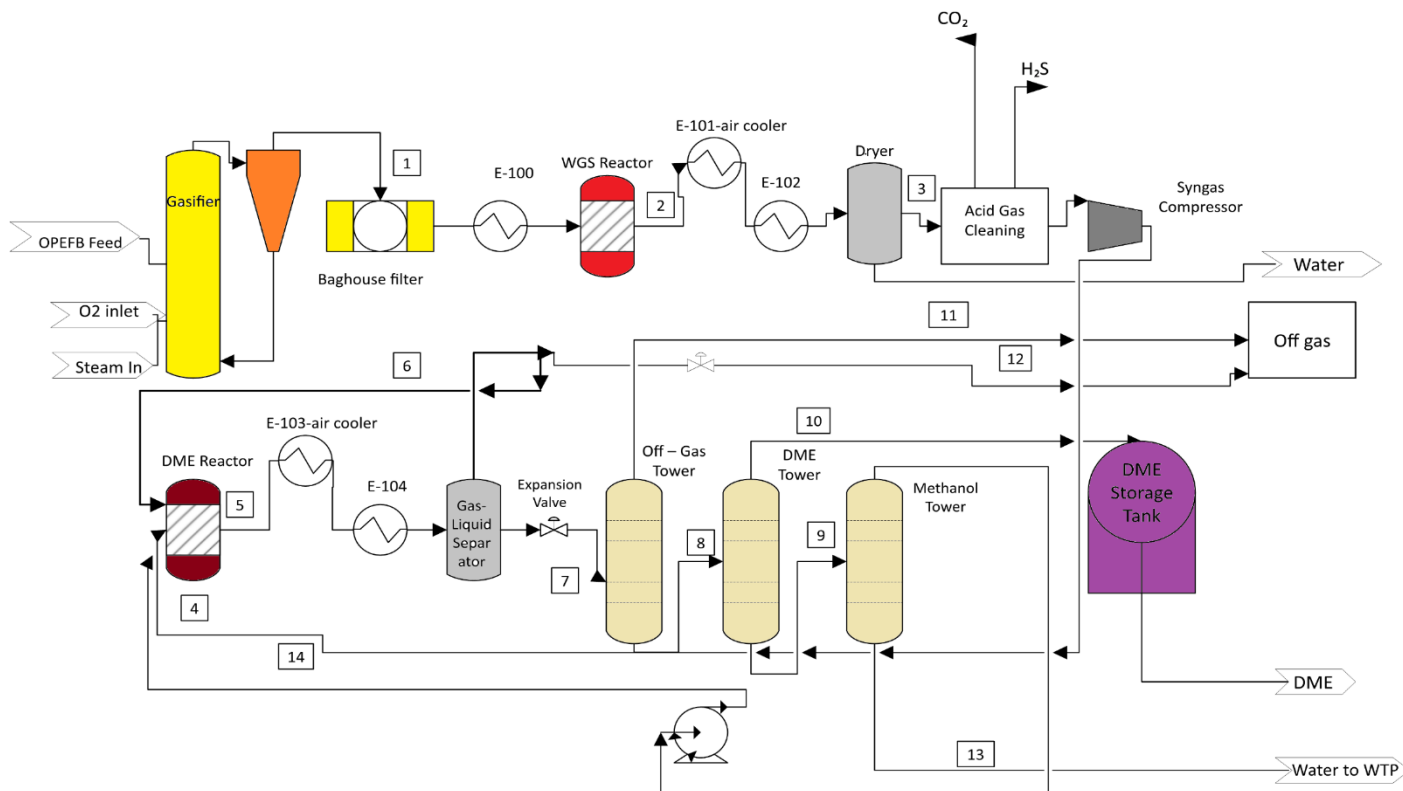


Fig. 3 Simplified process flow diagram (PFD) of OPEFB-based bio-DME production.

2.3 Economic assessment

It was assumed that the DME market is already available to substitute for diesel at a nearby mining company. The selling price of OPEFB-based bio-DME is assumed to follow a formula provided by the Indonesian Ministry of Energy and Mineral Resources (MEMR), where the formula for high-quality diesel follows MOPS (Mean of Platts Singapore) or Argus plus Rp2,000/litre + Margin (10% of base price); therefore, the selling price used is USD 737 per tonne of OPEFB-based bio-DME, based on the average MOPS price in August 2025 and the formula given by the Indonesian MEMR [38, 39]. At the same time, the diesel price used for comparison was based on the non-subsidy/industrial diesel price in August 2025, which was USD 1,560 per tonne [40] (USD 1 = Rp16,500).

The Capital Expenditure (CAPEX) of the DME plant follows the direct synthesis process of biomass to DME, where the DME plant serves as a reference, being a biomass-based DME plant with a production capacity of 392 tonnes/day of DME [41]. The DME plant cost of this OPEFB-based bio-DME plant in East Barito, Central Kalimantan, can be found using (3) [42].

$$C_B = C_A \left(\frac{S_B}{S_A} \right)^e \quad (3)$$

Where e is the scaling exponent, C_B is the approximate cost of equipment having size S_B (could be any unit), and C_A is the known cost of equipment having size S_A (same unit as S_B). The scaling exponent used is 0.7 [43].

The Chemical Engineering Plant Cost Index (CEPCI) is used to update DME plant costs to the current year; the updated cost can be calculated using (4).

$$Cost_a = Cost_b \times \left(\frac{CEPCI_a}{CEPCI_b} \right) \quad (4)$$

Where a and b denote the most recent year (2024) and the base year (2010), the reference year for the leading equipment was 2010, and the index used for the current year is 2024. The CEPCI values in 2010 and 2024 (average from January to June 2024) are 550.8 and 799.1, respectively [44].

The economic modelling in this study adopts an "Nth-plant" assumption, utilizing a scaling factor of 0.7 derived from a reference biomass-to-DME facility in the Netherlands [41, 45]. This approach assumes that the technology has matured beyond the "First-of-a-Kind" pioneering phase, thereby avoiding the significant contingency costs associated with pilot technologies. Given that biomass gasification and DME synthesis are mature technologies in their own right, the integration risk is considered manageable. However, the application of the scaling law inherently assumes that feedstock characteristics are similar between the reference plant (woody biomass) and the proposed OPEFB-based bio-DME plant. While the calorific values are comparable, OPEFB presents unique handling challenges due to its fibrous nature and high alkali content, which can affect gasifier maintenance intervals. Therefore, while the Nth-plant assumption provides a baseline for feasibility, the calculated CAPEX result should be viewed as a Class 4 estimate ($\pm 30\%$ accuracy) [43], suitable for strategic decision-making but requiring refinement for Front End Engineering Design (FEED).

The DME plant, used as a reference for DME plant cost calculations, was located in the Netherlands. The plant cost was also adjusted with the location factor. The location factor adjustments for the Netherlands and Indonesia are 1.23 and 0.89, respectively [42, 46].

The land cost was also part of CAPEX. The average price of land in Tamiang Layang, East Barito, was IDR 500,000 per square meter (approximately USD 27.59 per square meter, based on the exchange rate of IDR 16,500 = USD 1). The CAPEX was validated using a specific CAPEX and was used for comparison with other similar studies. Specific CAPEX is CAPEX per heating value of DME product, and the heating value is expressed in MW_{th} (heating value of DME is 28.43 MJ/kg). The woody biomass used as raw material for the DME plant in the Netherlands was dried using a dryer; hence, the base cost included the dryer unit to reduce the biomass's water content to 50%.

Complete cost estimates covered many things. Estimated variable costs covered are as follows: raw material; utility costs, including: steam, compressed air, refrigeration, electricity; water treatment or water treatment costs; labor costs; maintenance cost; insurance and taxes; factory overhead costs, all fees on process facilities that cannot be charged into other costs; expenses related to sales and marketing; research and development costs; and administrative costs [47, 48].

The system boundary for this techno-economic assessment is defined strictly as a "cradle-to-plant-gate approach". This boundary starts with the collection and transportation of OPEFB feedstock (within a 100 km radius) and ends at the plant gate, with the production of bio-DME ready for delivery. The economic model, therefore, encompasses only capital expenditures (CAPEX) and operational expenditures (OPEX) associated with feedstock acquisition, pretreatment, gasification, syngas cleaning, DME synthesis, and purification. Downstream infrastructure and end-user modifications, including localized fuel distribution networks, pressurized storage at the mine site, and heavy-duty engine retrofit costs, are explicitly excluded from the plant's financial model. However, because these end-user transition costs are critical to the overall feasibility of substituting diesel, their financial implications for fleet operator adoption are analyzed separately in the discussion.

The feasibility of the DME plant can be determined by using two key indicators: Net Present Value (NPV) and Internal Rate of Return (IRR). The values of NPV and IRR can be found using the Microsoft Excel function, based on equations (5) and (6). Table 3 shows the basic assumptions used in economic feasibility calculations.

$$NPV = \left(\sum_{t=1}^{t=n} \frac{C_t}{(1+i)^t} \right) - I \quad (5)$$

$$\left(\sum_{t=1}^{t=n} \frac{C_t}{(1+IRR)^t} - I \right) = 0 \quad (6)$$

Where C_t is the net cash flow at time t , t is the time of cash flow, n is the lifetime of the OPEFB-based bio-DME plant, i is the discount rate, and IRR is the internal rate of return. PP is the payback period. I is the initial investment, and AI is the annual income. The discount rate, or minimum acceptable rate of return (MARR) for investment purposes, is the prevailing loan interest rate in Indonesia. This interest rate was used as the desired expected return for the construction of the OPEFB-based bio-DME factory.

Regarding operational expenditures (OPEX), the baseline maintenance cost outlined in Table 3 was assumed to be 2.5% of the total CAPEX. This figure aligns with standard chemical engineering heuristics for solid-handling facilities [47]. It is consistent with recent techno-economic assessments of OPEFB-to-DME plants in Indonesia [17], which model annual fixed manufacturing costs at approximately

5% of CAPEX, with maintenance typically accounting for up to 40% of manufacturing cost [49, 50], where the OPEFB-to-DME plants' techno-economic assessment was around 2% of CAPEX. However, it is critical to acknowledge the feedstock's unique chemical properties. OPEFB contains significantly higher alkali metal content [51] when compared to conventional woody biomass. During high-temperature gasification, these alkali components can cause severe slagging, fluidized-bed agglomeration, and accelerated corrosion of downstream equipment. Consequently, actual maintenance and repair bills may face upward pressure as equipment degrades faster than in wood-fed baseline models. While this study utilizes 2.5% as a deterministic baseline to represent normalized fixed manufacturing costs, future Front End Engineering Design (FEED) stages for OPEFB-specific plants must incorporate higher OPEX contingencies to account for these accelerated wear rates.

Table 3 Assumptions used in the economic feasibility assessment.

Description	Value	Unit
Operational Parameters		
DME plant capacity	192	Tonne/Day
Plant Lifetime [52]	30	Year
Operational day [23]	328.5	Days
Revenue and cost during startup [52]	Revenue: 50%; Variable cost: 75%; Fixed cost: 100%	% of normal
Financial Parameters		
Debt-Equity Structure	70:30	%
Loan Term	10	Year
Loan Interest [53]	8	%
Tax Rate [54]	25	%
Salvage Value	0	%
Minimum Acceptable Rate of Return (MARR) [4]	8	%
Currency Exchange Rate	16,500	IDR/USD
Operating Expenditures (OPEX)		
Repair and Maintenance Cost [45]	2.5	% of CAPEX
Administration and Other Costs [54]	0.5	% of CAPEX
Utility Cost [54]	8	USD/tonne-DME
Market Pricing Assumptions		
OPEFB Selling Price	13.51	\$/Ton
Diesel Selling Price	1,560	\$/Ton
DME Selling Price	737	\$/Ton

2.4 Diesel budget saving

Cost savings and diesel consumption reductions can be estimated by comparing the selling price of OPEFB-based bio-DME with the price of non-subsidy diesel for coal mining in Kalimantan.

Table 4 OPEFB waste at a 100 km radius from Tamiang Layang.

Palm oil mill capacity (tonne/hour)	OPEFB waste (tonne/day)	Number of palm oil mills	OPEFB total waste (tonne/day) (Eff = 80% [17])
30	165.6	2	264.96
45	248.4	1	198.72
60	331.2	2	529.92

The reduction in diesel consumption can also be estimated by comparing OPEFB-based bio-DME production with demand for non-subsidy diesel in nearby coal mining areas. The scenario for selling OPEFB-based bio-DME as a diesel substitute differs from that for DME as an LPG substitute. OPEFB-based bio-DME is assumed to be distributed directly from the factory, without prior blending, to the nearby mine site, as it can be used 100% directly as fuel in diesel engines with slight modifications to the fuel distribution line, primarily to address its low lubricity and viscosity [15].

2.5 Sensitivity analysis

To assess the impact of potential changes on the project's feasibility, a sensitivity analysis must be conducted. The changes to be investigated here include fluctuations in product selling prices, raw material prices, factory capacity, and capital costs. The feasibility parameter used in this sensitivity analysis is NPV, as it is directly related to the investment's rate of return. Sensitivity analysis will be conducted on the Price of OPEFB raw materials, plant capacity, capital costs, and the selling price of OPEFB-based bio-DME. It is important to note that this study utilizes a deterministic approach. The sensitivity analysis identifies threshold values (break-even points) for individual variables. However, it does not account for the probabilistic distribution of simultaneous market changes (e.g., a simultaneous drop in diesel prices and rise in feedstock costs), which would require a Monte Carlo simulation.

2.6 Indicative carbon abatement cost by replacing diesel with DME

The simplified carbon abatement cost was calculated using (7).

$$CAC = \frac{AC_{DME} - AC_{Diesel}}{ADieselCO_2 - ADMECO_2} \quad (7)$$

Where AC_{DME} is the annualized cost of DME, AC_{Diesel} is the annualized cost of Diesel, $ADieselCO_2$ is the annual CO_2 from diesel, and $ADMECO_2$ is the annual CO_2 from DME.

The CO_2 value for diesel is 3.9 kg CO_2 -eq/kg-diesel, and the annual value is obtained by multiplying the diesel CO_2 emission by the diesel quantity replaced with DME. Since the DME heating value is lower than diesel, less diesel is required per mass unit, and the diesel substituted is calculated as the DME production quantity in kg per annum divided by 1.5, since DME has a lower energy density than diesel [9]. OPEFB-based bio-DME life cycle CO_2 -eq emission is 1.75 kg CO_2 -eq/kg-DME [16], and the annual CO_2 value was obtained by multiplying the CO_2 per kg OPEFB-based bio-DME by annual OPEFB-based bio-DME production.

3. Result and Discussion

3.1 Potential of OPEFB and production scenario

Table 4 from the previous study by Heryadi et al. [4] shows the potential OPEFB that can be collected in a single day from several POMs in the surrounding area of Tamiang Layang, East Barito, Central Kalimantan.

Table 5 Material balance and mol fraction of OPEFB-based bio-DME simulation.

Stream Name	Gasifier outlet	WGS reactor outlet	Dryer outlet	DME reactor Inlet	Distillation Inlet	DME	Methanol (Recycle)
Stream No.	1	2	3	4	7	10	14
Vapor Fraction	1	1	1	1	0.21	0	0
Temperature (°C)	400	400	25	243	-30.41	42.75	138
Pressure (kPa)	998	997	997	5,000	1,000	950	5,000
MolarFlow (kgmole/h)	1,314	1,486	1,476	1,307	399.9	174	25
Mass Flow (kg/h)	24,740	27,839	27,666	20,230	15,894	8,015	809
Heat Flow (MJ/h)	-85,420	-131,299	-147,414	-72,890	-106,156	-35,182	-57,521
Mol fraction (%)							
H ₂	30.16	38.27	38.52	43.52	0.31	0	0
CO	54.83	37.49	37.73	42.63	1.01	0	0
CO ₂	1.2	12.46	12.54	1.41	34.97	0	0
H ₂ O	0.89	0.98	0.34	0.39	3.93	0.25	0.1
CH ₄	11.58	10.32	10.39	11.73	10.69	0	0
H ₂ S	0.22	0.2	0.2	0	0	0	0
N ₂	0.3	0.27	0.27	0.3	0.13	0	0
CH ₃ OH	0	0	0	0	5.83	0.1	99.74
CH ₃ OCH ₃	0	0	0	0	43.12	99.64	0.16

Based on Nur [55] and Nur & Jusuf [6], the OPEFB waste produced is usually 23% of the amount of FFB processed. POMs operate 24 hours a day. According to Table 4, the total potential OPEFB that can be collected is 994 tonnes per day or 41 tonnes/hour. The OPEFB collected has a moisture content of 60% (as received), and on a dry ash-free (daf) basis, the OPEFB as raw material is 383 tonnes per day or 16 tonnes/hour. The daf basis OPEFB raw material mass flow rate was used as input to the process simulator. According to Heryadi et al. [30], 1 tonne of DME is produced for every 2 tonnes of OPEFB raw material (daf basis), and on an as-received basis, 5 tonnes of OPEFB will produce 1 tonne of DME [17, 45]. This ratio is used as a standard to validate the simulation used to determine the material balance in Aspen HYSYS. Based on the references, 192 tonnes/day of DME is produced from 383 tonnes/day of OPEFB daf-based input.

3.2 Simulation result and material balance

Based on the process simulation results, the material balance and flow composition are obtained as shown in Table 5. The H₂/CO ratio in stream no. 4 is 1 (H₂/CO = 1), which is required for one-step DME synthesis according to JFE technology. The OPEFB-based bio-DME produced is 8,015 kg/h. The bio-DME obtained from the DME tower has a purity of 99.6%, exceeding 99%, and is within the range reported in several previous studies [56–59]. The total yield of OPEFB-based bio-DME is consistent with several other studies on the OPEFB-to-DME yield ratio, which report a ratio of raw material as received (wet basis) to product of approximately 5 to 1. The ratio of raw material to product (daf basis) is 2 to 1 [17, 30, 41]. In this study, CO conversion is within the range of other studies, which show CO conversion of 90% or more [36, 56].

3.3 Economic evaluation result

Capital expenditure (CAPEX)

In the construction of this OPEFB-based bio-DME plant, it is assumed that an area of 30,380 m² is required for fuel storage, handling, and drying, as well as a syngas plant and a DME production facility from syngas. This area assumption is based on a study by Huisman et al. [45] on the land area requirements for a DME plant

based on biomass gasification. The capital cost (CAPEX) for this OPEFB-based bio-DME plant is based on 192 tonnes/day of DME. CAPEX investment data for the OPEFB-based bio-DME plant in East Barito is summarised in Table 6.

Table 6 CAPEX of OPEFB-based bio-DME factory.

Description	Unit	Value
Base Capacity [41,45]	tonne DME/day	392
Base Cost* [41]	million USD	299
DME plant capacity in East Barito	tonne DME/day	192
DME plant cost in East Barito	million USD	180
Land Cost	million USD	0.93
CAPEX	million USD	180.93
Specific CAPEX (Per MWth Product)	million USD/MWth	2.82

* Base cost in 2010, the exchange rate was Euro 1 = USD 1.327

Table 6 shows that land costs comprise only a small portion of CAPEX, at 0.51%, despite the large area required for building an OPEFB-based bio-DME plant. Land costs vary by DME plant location, ranging from 0.1% to 0.6% [17, 45]. The specific CAPEX of the OPEFB-based bio-DME plant in East Barito is still within the range of other studies with the same production route. A study conducted by Parbowo et al. [17] shows that the specific CAPEX is USD 2.74 million/MW_{th}. Studies conducted by Larson et al. [48] and Kreutz et al. [60] show that the specific CAPEX is USD 2.91 million per MWth and USD 2.97 million per MWth, respectively.

Operating expenditure (OPEX)

The operating costs or OPEX of this OPEFB-based bio-DME plant consist of the cost of OPEFB raw materials, labour, maintenance and repairs, utilities, depreciation, administration, and other costs. The annual OPEX of the OPEFB-based bio-DME plant is shown in Table 7.

Table 7 shows that the annual OPEX is USD 16.69 million, dominated by maintenance, depreciation, and raw material costs. Of the operating cost components, depreciation and capital-related costs are the most significant contributors to the OPEFB-based bio-DME plant's operations, followed by maintenance and repair costs,

raw material costs, administrative and other costs, utility costs, and labour costs. Other techno-economic or economic studies also show a similar pattern, in which capital-related operating cost components consistently dominate other cost components [4, 17, 45].

Table 7 OPEX of OPEFB-based bio-DME factory.

Cost type*	Cost Component	Cost per annum (million USD)
VC	Workforce and supervision [61]	0.33
VC	Repair and maintenance (2.5% of CAPEX) [45]	4.52
VC	Raw material cost (OPEFB) [4]	4.41
VC	Utility cost (water, refrigerant, water treatment) at USD 8 per tonne DME [54]	0.50
FC (non-cash)	Depreciation (straight line)	6.03
FC	Administration and other costs (0.5% of CAPEX) [54]	0.90
	Total variable cost	9.76
	Total fixed cost	6.93
	Total operating cost	16.69

*VC is a variable cost, and FC is a fixed cost.

Economic feasibility

The feasibility analysis was conducted using NPV and IRR indicators. Table 8 presents the results of the economic feasibility evaluation for OPEFB-based bio-DME as a diesel fuel substitute. The construction of this DME plant requires CAPEX of USD 180.93 million and OPEX of USD 16.69 million per year. Based on the results shown in Table 8, the OPEFB-based bio-DME plant is feasible to build, as the NPV is positive and the IRR exceeds the MARR of 8%. An IRR of 17% indicates that constructing a DME plant is a feasible option. The construction of an OPEFB-based bio-DME plant is deemed feasible if the IRR exceeds the MARR of 8%. A plant is considered feasible if its NPV is > 0. With an NPV value of USD 92.99 million, this DME plant is feasible to build, and the DME produced is entirely used as a substitute for diesel fuel.

While the economic model demonstrates strong feasibility, the commercial viability of this Nth plant relies heavily on the assumption of a stable industrial off-taker. Relying on a single large-scale mining operation as the primary buyer introduces significant demand risk. If the mining operation scales down or delays its transition to DME-retrofitted trucks, the plant could face severe revenue shortfalls. To mitigate this single-buyer risk and ensure the project's bankability for debt financiers, the DME producer must secure long-term, volume-guaranteed contractual arrangements prior to reaching the Final Investment Decision (FID). Additionally, establishing a secondary market strategy, such as distributing excess DME to the regional LPG blending market, would provide a critical buffer against localized fluctuations in industrial demand.

Table 8 Economic feasibility evaluation result.

Parameter	Unit	Value
CAPEX	million USD	180.93 (70% loan and 30% equity)
OPEX	million USD/year	16.69
Total Income	million USD/ year	46.48
Loan Payment	million USD/year	13.68 (10-year loan)
NPV	million USD	92.99
IRR	%	17% (equity IRR)

3.4 Diesel Consumption Reduction

Table 9 shows the consumption of non-subsidy diesel for the nearby coal mine and OPEFB-based bio-DME produced at the plant in East Barito. Because DME has a lower calorific value than diesel, diesel's price must be based on its calorific value, and the price calculation based on calorific value is presented in Table 9.

Table 9 Results of non-subsidy diesel saving.

Descriptions	Unit	Value
Diesel		
Price of Diesel (weight basis)	USD/tonne	1,560
Price of Diesel (LHV basis)	USD/MJ	0.036
DME		
DME ex-factory price (weight basis)	USD/tonne	\$737
DME ex-factory price (LHV basis)	USD/MJ	\$0.026
Diesel demand of the nearby coal mine (weight basis)	tonne/year	666,667
Diesel demand of the nearby coal mine (LHV basis)	GJ/year	28,676,000,000
DME from the plant in East Barito	tonne/year	63,072
DME as a substitute for Diesel Equivalent	GJ/year	1,793,136.960
Saving of non-subsidy diesel fuel per tonne	USD/tonne	0.0103
Saving of non-subsidy diesel fuel per year	Million USD/year	18.55

The calorific values of diesel and DME are 43 MJ/kg and 28.43 MJ/kg, respectively [9, 16]. Further cost savings can be achieved by lowering the price of OPEFB-based bio-DME to a level where the IRR remains above 8%, and the NPV is positive. Using OPEFB-based bio-DME can reduce demand for non-subsidy diesel at the nearby coal mine by approximately 6.25%. The savings from DME's calorific value relative to diesel are USD 18.55 million per year. The savings benefit the coal mining company by reducing its energy costs, specifically diesel consumption. An increase in the size and number of plants by up to 16 times the current capacity is required to completely replace diesel consumption at the nearby coal mine with OPEFB-based bio-DME. To further reduce consumption and costs, the price of OPEFB-based bio-DME needs to be adjusted downward without compromising the feasibility of OPEFB-based bio-DME plants.

3.5 Sensitivity analysis

A sensitivity analysis of OPEFB-based bio-DME was conducted across variations in OPEFB feedstock price, ex-factory OPEFB-based bio-DME price, factory capacity, and CAPEX. The results of the sensitivity analysis are presented in Figure 4. Figure 4(a) shows the correlation between OPEFB price and NPV. The OPEFB-based bio-DME plant remains feasible with an NPV value greater than 0. The NPV value increases when the OPEFB price decreases, and vice versa. When the NPV decreases, the OPEFB price increases. The correlation between NPV and OPEFB price is positive, as seen in Figure 4(a). The OPEFB price of USD 6.76 per tonne corresponds to an NPV of USD 111.38 million, the OPEFB price of USD 13.51 per ton corresponds to an NPV of USD 92.99 million, the OPEFB price of USD 20.27 per tonne corresponds to an NPV of USD 74.59 million, and the OPEFB price of USD 27.02 per tonne corresponds to an NPV of USD 56.20 million.

Sensitivity analysis was also performed with variations in capacity. Since the current capacity is operating at 100% OPEFB feed, a sensitivity analysis was performed for lower OPEFB feeds of 20%, 25%, and 50%.

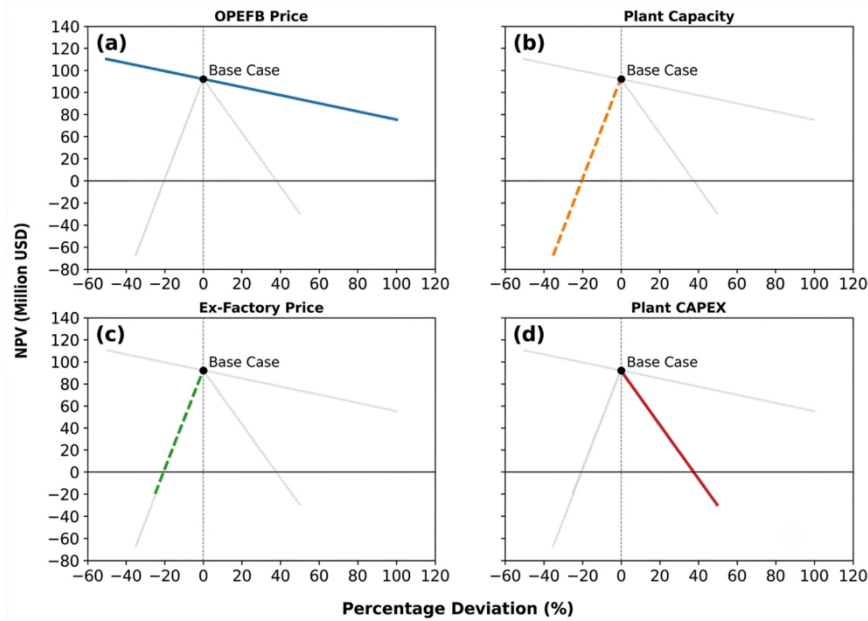


Fig. 4 Sensitivity analysis results (a) OPEFB price variation (b) Capacity variation (c) Ex-factory bio-DME price variation (d) CAPEX variation.

The OPEFB-based bio-DME plant remains feasible at lower capacities of 20% and 25%. The NPV is negative when the DME plant capacity is 50% or lower, as seen in Figure 4(b). Specifically, break-even analysis explicitly identifies a critical threshold for capacity utilization at approximately 74% (assuming baseline diesel prices). The plant must operate at or above this 74% threshold to maintain financial viability, where $NPV \geq 0$. This provides a robust operational buffer of 26%, indicating a high tolerance for unplanned maintenance outages or seasonal OPEFB supply chain disruptions. The baseline model assumes an OPEFB feedstock price of USD 13.51/tonne. This price essentially covers the cost of collection and transportation, as the waste itself often has negative value at the mill. However, as demand for biomass energy rises in Indonesia, a competitive market for OPEFB may emerge. Sensitivity calculations indicate that the project remains viable even if feedstock prices rise by up to 250%. This high tolerance is due to the fact that feedstock costs contribute relatively little to the total OPEX compared to capital depreciation and maintenance. This suggests that the project is feedstock-secure, provided long-term off-take agreements with local palm oil mills are secured. Fluctuations in ex-factory OPEFB-based bio-DME prices due to changes in global diesel prices also need to be analysed. Therefore, a sensitivity analysis was conducted for ex-factory OPEFB-based bio-DME prices that were 10%, 20%, and 30% lower than the base case. Figure 4(c) shows that the plant remains viable if the ex-factory OPEFB-based bio-DME price is 20% below the initial price, whereas if the price is 30% below the initial price, the NPV becomes negative. This 30% lower price is equivalent to USD 516 per tonne. The project's revenue is directly tied to the avoided cost of industrial diesel. The baseline assumes a non-subsidy diesel price of USD 1,560/tonne. If global crude oil prices were to contract, reducing industrial diesel prices to USD 1,000/tonne, the project's revenue stream would contract significantly. Analysis shows that the Break-even Diesel Price, at which the OPEFB-based bio-DME plant's NPV hits zero, is approximately USD 1,150/tonne, or equivalent to USD 0.026/MJ (LHV basis). This break-even diesel price is a critical risk factor. Given that mining operations in remote Kalimantan pay a premium for fuel due to logistics, the actual diesel price faced by the end-user is likely to remain above this floor, insulating the project from minor global oil price dips. However, a structural collapse in fossil fuel prices remains the single most significant threat to the plant's financial viability.

Sensitivity to CAPEX was also evaluated, and a sensitivity analysis was conducted with CAPEX set to 25% and 50% higher than the base case. Sensitivity to CAPEX was evaluated for inflation adjustments affecting equipment prices and other related costs during the construction phase. Figure 4(d) illustrates that an increase in CAPEX of up to 50% is not economically feasible for this OPEFB-based bio-DME plant. An increase in CAPEX to 25% corresponds to an NPV of USD 32.28 million, and an increase in CAPEX to 50% corresponds to an NPV of USD -28.42 million. Based on this trajectory, the break-even analysis explicitly identifies the maximum tolerable CAPEX threshold at approximately 38.3% (a total CAPEX of roughly USD 250 million), at which the project's NPV hits exactly zero. First-of-a-kind biomass plants often experience capital cost overruns. Under this scenario, the NPV becomes negative as CAPEX increases. This erosion underscores the need for strict Engineering, Procurement, and Construction (EPC) controls. The project's sensitivity to CAPEX is higher than to OPEX, confirming that the economic barrier is primarily the upfront investment rather than the ongoing operational cost.

While this sensitivity assessment focuses on four primary techno-economic pillars, these variables inherently capture broader market and operational uncertainties. Specifically, the sensitivity of the DME selling price serves as a direct proxy for evaluating global diesel price scenarios, while the 74% capacity utilization threshold effectively models limits on plant availability. Other highly dynamic or spatial factors, such as variations in the discount rate, seasonal fluctuations in feedstock moisture, and extended transport distances, which fall outside the deterministic 'cradle-to-plant-gate' boundary of this economic model, are addressed separately in the study's limitations section.

Despite the previous One At a Time (OAT) sensitivity analysis, which provides valuable knowledge about the individual operational parameter, real-world investment risk often involves adverse market conditions simultaneously. To evaluate the risk associated with the real-world investment, a combined downside scenario was analyzed. As illustrated in Figure 5, by assuming a perfect storm happened, especially the dropping of DME price at 20% (which represents the alternative diesel price), higher CAPEX at 25%, and reduction of DME plant capacity at 75% from its original intended capacity, the project economy declines drastically, resulting in an NPV value of

USD -100.44 million and IRR for this case is -0.03% (combined shock). Cumulative revenue losses mainly drive the severity of this combined downside scenario, as decreases in product price and production volume reduce almost all gross operational revenue. At the same time, higher, bloated CAPEX is very burdensome to capital recovery costs. The downside analysis shows that, though the project appears profitable under basic conditions, combined market and operational shocks pose a serious risk to its feasibility. This downside analysis demonstrates that while the project is highly lucrative under baseline conditions (NPV = USD 92.99 million), compounded market and operational shocks pose a critical risk to project bankability, further underscoring the necessity of rigid EPC contracts and fixed-price off-take agreements.

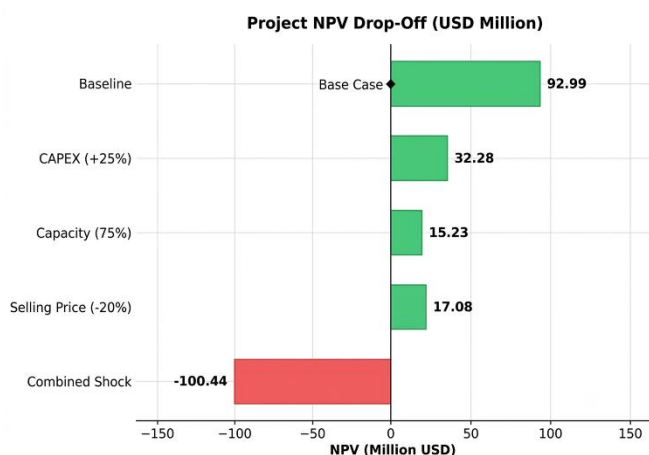


Fig. 5 Sensitivity analysis – Combined downside analysis.

These quantitative thresholds become the standard for the project's risk mitigation strategy. Before the final investment decision (FID) is made, the investor must ensure that several considerations are met. The considerations to be met include a strict, fixed-price EPC contract to prevent CAPEX bloating, an agreement on long-term raw material supply to keep operations above their 74% capacity threshold, and a fixed-price off-take agreement with the mining sector. The lowest price of diesel threshold determination at USD 1,150/tonne underscores the importance of supporting policies, such as a carbon price mechanism or a minimum price for bio-DME, to minimize risk and accelerate the implementation of bio-DME technology in a remote mining location.

3.6 System-level cost implications for diesel substitution

However, transitioning a mining fleet to DME is not without technical hurdles. The low viscosity of DME compared to diesel [9] poses a risk of leakage in conventional fuel pumps and injectors. In contrast, its lower lubricity necessitates the use of additives or specialized wear-resistant coatings. Storage is another consideration; DME must be stored at moderate pressure, similar to LPG. While mining sites are well-positioned to adapt to this, given their familiarity with LPG, the fuel tanks on mining trucks would need to be replaced with pressurized vessels. From an economic standpoint, these dedicated retrofit kits that cover specialized injectors, seals, and pressurized tanks represent a significant 'switching cost' for the end-user. Estimated retrofit costs at approximately EUR 15,000 or USD 17,200 per truck, based on heavy-duty alternative fuel conversion benchmarks [62], were not included in the plant CAPEX.

Furthermore, because DME possesses physical properties similar to LPG, the mining operator must also invest in specialized, pressurized mid-stream storage and distribution infrastructure.

To contextualize this switching cost, assuming a high-end retrofit cost at USD 17,200 amortized over a typical 5-year operational life, the annualized hardware cost per truck is USD 3,440. Based on recent operational baselines for medium-duty mining dump trucks in East Kalimantan, Indonesia [63], heavy equipment typically operates 3,000 hours annually, with average fuel consumption ranging from 36 to 39 liters per hour. Adopting a slightly conservative baseline of 36 liters per hour for this study, a standard mining truck consumes approximately 108,000 liters or 91.8 tonnes of diesel annually. At the baseline price of USD 1,560/tonne, this equates to an annual fuel expense of USD 143,208. To offset the annualized retrofit cost and maintain the fleet operator's Return on Investment (ROI), the OPEFB-based bio-DME must yield an equivalent annual saving. Consequently, the fuel must be priced at a marginal discount of roughly 2.4% (USD 3,440/USD 143,208) relative to energy-equivalent diesel.

As detailed in Section 3.4 and Table 9, the 63,072 tonnes/year of bio-DME produced by the plant displaces the energy equivalent of approximately 41,700 tonnes of diesel per year (LHV basis). This substitution generates a net annual saving of USD 18.55 million for the mining company after paying the bio-DME ex-factory price. This saving represents a 6.25 % reduction in the mine's total non-subsidy diesel consumption. At the fleet level, the USD 18.55 million in annual savings can fully cover the annualized retrofit cost (USD 3,440 per truck) for more than 5,390 trucks, while still leaving the operator with a substantial net positive cash flow. Even after accounting for additional midstream storage and distribution infrastructure, the fuel-cost savings provide a very strong economic incentive for the mining company to adopt DME. Further cost savings can be achieved by negotiating a lower bio-DME selling price, while ensuring that the plant's IRR remains above the 8% MARR and that the NPV remains positive.

Despite these retrofitting requirements, DME offers a higher cetane number (55–60 versus 40–55 for diesel), providing quieter engine operation, improved thermal efficiency, and potential benefits to engine life [9]. Although its lower energy density requires larger tanks, the short, fixed-loop drive cycles typical of mining trucks substantially mitigate range concerns compared with other low-density alternative fuels.

3.7 Indicative carbon abatement cost

Beyond the mechanical transition, the estimated indicative carbon abatement cost by substituting diesel with OPEFB-based bio-DME is highly favorable at approximately USD -617 per tonne of CO₂ avoided. A negative carbon abatement cost indicates that replacing fossil diesel with OPEFB-based bio-DME is not only environmentally beneficial but also economically superior to the business-as-usual scenario. As defined in Equation (7), this figure was calculated by comparing the annualized plant cost (USD 32.76 million, combining OPEX and annualized CAPEX at an 8% discount rate) against the cost of purchasing energy-equivalent industrial diesel (USD 65.16 million), divided by the estimated 52,525 tonnes of annual CO₂ emissions avoided by displacing the fossil fuel.

It must be emphasized that this highly favorable indicative carbon abatement cost is based on simplified assumptions of direct fossil fuel displacement and is limited to plant operations. Under full Life Cycle Assessment (LCA) conditions, incorporating upstream OPEFB logistics, fertilizer inputs, indirect land-use changes, and downstream DME distribution would introduce supply-chain carbon penalties, likely reducing the absolute magnitude of the abatement benefit. Nevertheless, Bio-DME is still expected to remain highly competitive against fossil diesel baselines. This resilience is supported

by prior life-cycle studies, such as Lecksiwilai et al. [16], which confirm that OPEFB-based bio-DME yields substantial net CO₂-equivalent reductions and eliminates localized particulate matter due to its lack of carbon-carbon bonds. Ultimately, while the direct, localized air quality and ESG benefits are evident, integrating this techno-economic framework with a dynamic, full-spatial LCA remains a critical avenue for future research.

3.8 Policy implications and environmental, social, and governance (ESG) alignment

Beyond the economic assessment results, substituting 6.25% of the mining operation's diesel demand yields substantial local environmental benefits. Because the current plant capacity (192 tonnes/day) replaces only this fraction, achieving full decarbonization for this specific mine would require approximately 16 similar production trains. This highlights the strategic need for a clustered industrial approach rather than standalone pilots. Unlike fossil diesel, which contains sulfur even in low-sulfur variants, DME is synthetically produced and sulfur-free; hence, SO_x emissions from mining equipment could be eliminated from the portion of the fuel substituted. Furthermore, the oxygenated nature of the DME molecule ensures smokeless and clean combustion, significantly reducing Particulate Matter (PM) emissions [9, 14]. For open-pit mining operations where air quality and visibility are part of safety, health, and environmental concerns, this reduction in PM is a non-monetary but operationally critical benefit. Moreover, unlike diesel, which poses severe risks of soil and groundwater contamination when spilled, DME is non-toxic, non-carcinogenic, and biodegradable [64, 65]. In the event of a leak, it evaporates rapidly without polluting the surrounding ecosystem, a crucial advantage for mining sites operating near sensitive watersheds and villages in Kalimantan.

This decarbonization potential aligns directly with the Green Mining initiative, in which mining companies have increasingly considered adopting Environmental, Social, and Governance (ESG) standards, particularly to enhance their competitiveness [66]. For mining companies targeting net-zero compliance, this fuel switching offers a tangible mechanism for reducing Scope 1 emissions and supports environmental assessments, effectively monetizing environmental compliance. Furthermore, the project aligns with Indonesia's Rencana Umum Energi Nasional (RUEN) 2017, or the National Energy General Plan, filling a critical gap in the second-generation biofuel roadmap [7]. Unlike the current reliance on CPO-based biodiesel, which carries the policy risk of the "food vs. fuel" debate and exposure to CPO price spikes, OPEFB-based bio-DME utilizes a non-food waste residue. Reliance on OPEFB-based bio-DME allows mining companies to hedge against commodity volatility while supporting the circular economy.

Regarding electrification, while Battery Electric Vehicles (BEVs) are highly efficient for light-duty transport, they face significant thermodynamic and logistical constraints in heavy-duty mining. The massive weight of the battery required to power more than 100 tonnes of coal-hauling trucks drastically reduces payload capacity, directly impacting mining productivity [67]. Similarly, while hydrogen offers excellent mass-based energy density, it suffers from exceptionally low volumetric density. Transporting and storing hydrogen at remote locations in Kalimantan requires either cryogenic liquefaction (-253°C) or ultra-high-pressure vessels (700 bar), which represent logistical complexities and CAPEX barriers that are currently prohibitive for off-grid mines [68, 69]. In contrast, DME liquefies at mild pressure (5–6 bar), mimicking the well-established logistics of LPG [4, 64]. Due to the limitations of BEVs and hydrogen-fueled fleets, OPEFB-based bio-DME emerges as a highly pragmatic benchmark for decarbonization.

Additionally, the case study's location in East Barito adds a geopolitical dimension; developing a clean energy hub there serves as a pilot for the new capital Nusantara or IKN support zones, demonstrating Kalimantan's transition from a fossil coal extractor to a renewable synthetic fuel producer.

3.9 Limitations and future works

While this assessment demonstrates the baseline viability of OPEFB-based bio-DME, certain boundary conditions related to biomass logistics limit the current model. The study assumes an aggregated OPEFB supply within a 100 km radius; however, the transportation cost modeling remains simplified. In practice, feedstock logistics are highly sensitive to seasonal supply variations in oil palm yields, which can dynamically affect the plant's capacity factor. Furthermore, the current analysis does not explicitly quantify the market dynamics of competing uses for OPEFB (e.g., existing local composting or direct boiler combustion) or the associated supply reliability risks over a multi-decade project lifespan. Because biomass logistics strongly dictate the ultimate financial feasibility and risk profile of localized bioenergy projects, future research must integrate dynamic supply chain modeling, geospatial routing, and seasonal feedstock sensitivity to refine these delivered cost assumptions.

In addition, while the deterministic techno-economic model, supported by OAT sensitivity analysis and a combined downside scenario, provides useful insights, it cannot fully capture the simultaneous interactions among multiple correlated uncertainties typical of real-world energy investments (e.g., volatile diesel prices, CAPEX overruns, and fluctuating plant capacity). Future research should therefore adopt probabilistic uncertainty analysis, such as Monte Carlo simulation, to generate probability distributions of the key feasibility indicators (NPV and IRR), quantify overall project risk exposure more comprehensively, and provide investors and policymakers with robust confidence intervals for decision-making under uncertainty.

4. Conclusion

This study demonstrates the economic feasibility of utilizing OPEFB to produce DME as a substitute for non-subsidy industrial diesel in the coal mining industry. The financial model yields a highly favorable NPV of USD 92.99 million and an IRR of 17%, performing well above the 8% MARR baseline. By dedicating the plant's production to a nearby coal mine, the project can displace 6.25% of the mine's annual diesel demand. Accounting for the calorific differences between the fuels, this substitution translates to significant energy cost savings of USD 18.55 million per year for the end-user.

However, sensitivity analysis indicates that the economic resilience of the OPEFB-based bio-DME plant is highly dependent on three variables: CAPEX, plant capacity utilization, and the ex-factory selling price of DME. To maintain financial viability, upfront CAPEX overruns must be strictly controlled and not exceed 38.3%. In comparison, plant operations must remain above a 74% capacity threshold to withstand potential disruptions to the feedstock supply chain.

Ultimately, this research confirms that OPEFB-based bio-DME should be viewed not merely as a waste-management strategy but as a critical component of Indonesia's energy transition. It successfully bridges the gap between abundant agricultural waste and the heavy-duty fuel needs of the archipelago's industrial backbone. Given the highly favorable estimated carbon abatement cost of USD -617 per tonne of CO₂ avoided, future work should focus on conducting a comprehensive, consequential LCA. Quantifying the exact life-cycle greenhouse gas reductions will allow future bio-synthetic fuel

projects to monetize these environmental benefits through formal carbon trading mechanisms, further enhancing their economic viability. Additionally, future techno-economic research should incorporate probabilistic uncertainty analyses, such as Monte Carlo simulations, to better capture interactions among volatile market variables and to fully evaluate stochastic investment risks under compounded downside scenarios. Overall, this study demonstrates a practical and scalable pathway for converting abundant agricultural waste into a low-carbon fuel, offering actionable insights for policymakers, mining operators, and practitioners seeking to advance industrial decarbonization and Indonesia's sustainable energy transition.

References

- [1] Hutrindo, E. Bioenergy Introduction Module [in Indonesian]. 1st edn. Pusdiklat Ketenagalistrikan, Energi Baru, Terbarukan, dan Konservasi Energi East Jakarta, 2015.
- [2] Basu, P. *Biomass Gasification and Pyrolysis*. Academic Press, 2010, doi: <https://doi.org/10.1016/B978-0-12-374988-8.00011-8>.
- [3] Heryadi, R., Uyun, A. S., Yandri, E., Nur, S. M. and Abdullah, K., Palm empty fruit bunch gasification simulation in circulating fluidized bed gasifier. *E3S Web of Conferences*. 67 (2018) 02043, doi: <https://doi.org/10.1051/e3sconf/20186702043>.
- [4] Heryadi, R., Widianarko, B. and Rahutami, I. A., Economic Feasibility of Dimethyl Ether from Oil Palm Empty Fruit Bunch as a Substitute for LPG in Indonesia. *Current Applied Science and Technology*. 23 (2023) 1-17, doi: <https://doi.org/10.55003/cast.2023.04.23.014>.
- [5] Afriyanti, D., Kroeze, C. and Saad, A., Indonesia palm oil production without deforestation and peat conversion by 2050. *Science of The Total Environment*. 557-558 (2016) 562-570, doi: <https://doi.org/10.1016/j.scitotenv.2016.03.032>.
- [6] Nur, S.M. and Jusuf, J. Shifting the Palm Oil Agroindustry Paradigm Towards Renewable Energy [in Indonesian]. PT Insan Fajar Mandiri Nusantara, 2014.
- [7] Rudy, H. and Budi, W., Bio-Dimethyl Ether from Oil Palm Empty Fruit Bunch and Sustainability Assessment of Bio-Dimethyl Ether: A Case Study in Indonesia. *CURRENT APPLIED SCIENCE AND TECHNOLOGY*. 22 (2021) 1-14, doi: <https://doi.org/10.55003/cast.2022.05.22.004>.
- [8] Oda, Y., Osafune, S., Ueda, H. and Fujimura, K., Clean Combustion Technology in Diesel Engines Operated with Dimethyl ether. *Technical Review Mitsubishi Heavy Industries Ltd*. 40 (2004) 2-6.
- [9] Park, S. H. and Lee, C. S., Applicability of dimethyl ether (DME) in a compression ignition engine as an alternative fuel. *Energy Conversion and Management*. 86 (2014) 848-863, doi: <https://doi.org/10.1016/j.enconman.2014.06.051>.
- [10] Himabindu, M. and Ravikrishna, R. V., Potential of bio-DME as a transportation fuel for India. *Journal of Renewable and Sustainable Energy*. 2 (2010) 052701, doi: <https://doi.org/10.1063/1.3489529>.
- [11] Wang, Y., Liu, H., Huang, Z. and Liu, Z., Study on combustion and emission of a dimethyl ether-diesel dual-fuel premixed charge compression ignition combustion engine with LPG (liquefied petroleum gas) as ignition inhibitor. *Energy*. 96 (2016) 278-285, doi: <https://doi.org/10.1016/j.energy.2015.12.056>.
- [12] Park, S. H., Yoon, S. H., Cha, J. and Lee, C. S., Mixing effects of biogas and dimethyl ether (DME) on combustion and emission characteristics of DME fueled high-speed diesel engine. *Energy*. 66 (2014) 413-422, doi: <https://doi.org/10.1016/j.energy.2014.02.007>.
- [13] McFarlan, A., Techno-economic assessment of pathways for electricity generation in northern remote communities in Canada using methanol and dimethyl ether to replace diesel. *Renewable and Sustainable Energy Reviews*. 90 (2018) 863-876, doi: <https://doi.org/10.1016/j.rser.2018.03.076>.
- [14] Tunå, P. and Hulteberg, C., Woody biomass-based transportation fuels – A comparative techno-economic study. *Fuel*. 117 (2014) 1020-1026, doi: <https://doi.org/10.1016/j.fuel.2013.10.019>.
- [15] Makoś, P., Słupek, E., Sobczak, J., Zabrocki, D., Hupka, J. and Rogala, A., Dimethyl ether (DME) as potential environmental friendly fuel. *E3S Web of Conferences*. 116 (2019) 00048, doi: <https://doi.org/10.1051/e3sconf/201911600048>.
- [16] Lecksiwilai, N., Gheewala, S. H., Sagisaka, M. and Yamaguchi, K., Net Energy Ratio and Life cycle greenhouse gases (GHG) assessment of bio-dimethyl ether (DME) produced from various agricultural residues in Thailand. *Journal of Cleaner Production*. 134 (2016) 523-531, doi: <https://doi.org/10.1016/j.jclepro.2015.10.085>.
- [17] Parbowo, H. S., Ardy, A. and Susanto, H., Techno-economic analysis of Dimethyl Ether production using Oil Palm Empty Fruit Bunches as feedstock – a case study for Riau. *IOP Conference Series: Materials Science and Engineering*. 543 (2019) 012060, doi: <https://doi.org/10.1088/1757-899X/543/1/012060>.
- [18] Borneonews. *Special Economic Zone to be Built in East Barito* [in Indonesian], <<https://www.borneonews.co.id/berita/154193-kawasan-ekonomi-khusus-akan-dibangun-di-barito-timur>> (2020).
- [19] Adaro Andalan Indonesia. *Adaro Andalan Indonesia*, <https://www.adaroindonesia.com/pages/view/Adaro_Minig.html> (2025).
- [20] Kontan. *Mining Fuel Costs Rise by 35%, EV Use Considered a Solution* [in Indonesian], <<https://industri.kontan.co.id/news/biaya-bahan-bakar-pertambangan-sampai-35-penggunaan-ev-dinilai-jadi-solusi>> (2025).
- [21] Heryadi, R., Nur, S. M., Putu Hikariantara, I., Suseno, D. and Viendyasari, M., The potential of bio-DME from oil palm empty fruit bunch in the Kalimantan region. *IOP Conference Series: Earth and Environmental Science*. 1282 (2023) 012047, doi: <https://doi.org/10.1088/1755-1315/1282/1/012047>.
- [22] Liputan6. *Pertamina Supplies 550,000 Kilograms of Fuel to Adaro Per Year - Liputan6.com Business* [in Indonesian], <<https://www.liputan6.com/bisnis/read/2315091/pertamina-pasok-bbm-adaro-550-ribu-kl-per-tahun>> (2015).
- [23] Montoya, J., Valdés, C., Chaquea, H., Pecha, M. B. and Chejne, F., Surplus electricity production and LCOE estimation in Colombian palm oil mills using empty fresh bunches (EFB) as fuel. *Energy*. 202 (2020) 117713, doi: <https://doi.org/10.1016/j.energy.2020.117713>.
- [24] Aziz, M., Prawisudha, P., Prabowo, B. and Budiman, B. A., Integration of energy-efficient empty fruit bunch drying with gasification/combined cycle systems. *Applied Energy*. 139 (2015) 188-195, doi: <https://doi.org/10.1016/j.apenergy.2014.11.038>.

- [25] Zhang, Y., Xiao, J. and Shen, L., Simulation of Methanol Production from Biomass Gasification in Interconnected Fluidized Beds. *Industrial & Engineering Chemistry Research*. 48 (2009) 5351-5359, doi: <https://doi.org/10.1021/ie801983z>.
- [26] Chen, P. C., Chiu, H.-M., Chyou, Y. P. and Yu, C. S., Processes simulation study of coal to methanol based on gasification technology. *World Academy of Science, Engineering and Technology*. 65 (2010) 988-996.
- [27] Clausen, L. R., Elmegaard, B. and Houbak, N., Technoeconomic analysis of a low CO₂ emission dimethyl ether (DME) plant based on gasification of torrefied biomass. *Energy*. 35 (2010) 4831-4842, doi: <https://doi.org/10.1016/j.energy.2010.09.004>.
- [28] Andersson, J., Lundgren, J. and Marklund, M., Methanol production via pressurized entrained flow biomass gasification – Techno-economic comparison of integrated vs. stand-alone production. *Biomass and Bioenergy*. 64 (2014) 256-268, doi: <https://doi.org/10.1016/j.biombioe.2014.03.063>.
- [29] Inayat, A., Ghenai, C., Naqvi, M., Ammar, M., Ayoub, M. and Hussin, M. N. B., Parametric Study for Production of Dimethyl Ether (DME) As a Fuel from Palm Wastes. *Energy Procedia*. 105 (2017) 1242-1249, doi: <https://doi.org/10.1016/j.egypro.2017.03.431>.
- [30] Heryadi, R., Uyun, A. S., Yandri, E., Nur, S. M. and Abdullah, K., Single stage dimethyl ether plant model based on gasification of palm empty fruit bunch. *IOP Conference Series: Materials Science and Engineering*. 532 (2019) 012009, doi: <https://doi.org/10.1088/1757-899X/532/1/012009>.
- [31] Doherty, W., Reynolds, A. and Kennedy, D. Simulation of a Circulating Fluidised Bed Biomass Gasifier using ASPEN Plus – A Performance Analysis, in A. Ziebig, Z. Kolenda, and W. Stanek (eds). in *Proceeding 21st International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*. (2008), 1241-1248, doi: <https://doi.org/10.21427/3aae-7t77>.
- [32] Parvez, A. M., Wu, T., Li, S., Miles, N. and Mujtaba, I. M., Bio-DME production based on conventional and CO₂-enhanced gasification of biomass: A comparative study on exergy and environmental impacts. *Biomass and Bioenergy*. 110 (2018) 105-113, doi: <https://doi.org/10.1016/j.biombioe.2018.01.016>.
- [33] Heryadi, R., Uyun, A. S., Yandri, E., Nur, S. M., Abdullah, K. and Anne, O., Biomass to methanol plant based on gasification of palm empty fruit bunch. *IOP Conference Series: Earth and Environmental Science*. 293 (2019) 012036, doi: <https://doi.org/10.1088/1755-1315/293/1/012036>.
- [34] Bolland, O. and Mathieu, P., Comparison of two CO₂ removal options in combined cycle power plants. *Energy Conversion and Management*. 39 (1998) 1653-1663, doi: [https://doi.org/10.1016/S0196-8904\(98\)00078-8](https://doi.org/10.1016/S0196-8904(98)00078-8).
- [35] Tavan, Y. and Khosravi Nikou, M. R., A novel distillation design for vapor phase dimethyl ether production process. *Asia-Pacific Journal of Chemical Engineering*. 9 (2014) 464-470, doi: <https://doi.org/10.1002/apj.1776>.
- [36] Ogawa, T., Inoue, N., Shikada, T. and Ohno, Y., Direct Dimethyl Ether Synthesis. *Journal of Natural Gas Chemistry*. 12 (2003) 219-227.
- [37] Chen, W.-H., Hsu, C.-L. and Wang, X.-D., Thermodynamic approach and comparison of two-step and single step DME (dimethyl ether) syntheses with carbon dioxide utilization. *Energy*. 109 (2016) 326-340, doi: <https://doi.org/10.1016/j.energy.2016.04.097>.
- [38] Ministry of Energy and Mineral Resources. *MEMR minister establish a Basic Price Formula for Calculating the Retail Selling Price of General Fuels, Gasoline and Diesel* [in Indonesian], <<https://www.migas.esdm.go.id/post/menteri-esdm-tetapkan-formula-harga-dasar-perhitungan-harga-jual-eceran-bbm-umum-jenis-bensin-dan-solar>> (2020).
- [39] Investing.com. *NYMEX Singapore GASOIL PLATTS Futures Historical Prices - Investing.com*, <<https://www.investing.com/commodities/nymex-singapore-gasoil-platts-c1-futures-historical-data>> (2025).
- [40] solarindustri.com. *Industrial Diesel Prices for B40 & MFO August 1-14, 2025* [in Indonesian], <<https://solarindustri.com/berita/harga-solar-industri-01-14-agustus-2025/>> (2025).
- [41] Van Rens, G. L. M. A., Huisman, G. H., De Lathouder, H. and Cornelissen, R. L., Performance and exergy analysis of biomass-to-fuel plants producing methanol, dimethylether or hydrogen. *Biomass and Bioenergy*. 35 (2011) S145-S154, doi: <https://doi.org/10.1016/j.biombioe.2011.05.020>.
- [42] Seider, W. D., Seader, J. D., Lewin, D. R. and Widagdo, S. *Product and Process Design Principles*. 3rd edn., John Wiley & Sons Inc, 2009.
- [43] Tsagkari, M., Couturier, J.-L., Kokossis, A. and Dubois, J.-L., Early-Stage Capital Cost Estimation of Biorefinery Processes: A Comparative Study of Heuristic Techniques. *ChemSusChem*. 9 (2016) 2284-2297, doi: <https://doi.org/10.1002/cssc.201600309>.
- [44] Maxwell, C. *Cost Indices – Towering Skills*, <<https://toweringskills.com/financial-analysis/cost-indices/>> (2025).
- [45] Huisman, G. H., Van Rens, G. L. M. A., De Lathouder, H. and Cornelissen, R. L., Cost estimation of biomass-to-fuel plants producing methanol, dimethylether or hydrogen. *Biomass and Bioenergy*. 35 (2011) S155-S166, doi: <https://doi.org/10.1016/j.biombioe.2011.04.038>.
- [46] Roest E. V. D. Waste Toilet paper to Electricity – A techno-economic feasibility study. Master Thesis, Universiteit Utrecht, Netherlands. (2016).
- [47] Peters, M. S., Timmerhaus, K. D. and West, R. E. *Plant Design and Economics for Chemical Engineers*. 5th edn., McGraw-Hill Chemical Engineering Series, 2003.
- [48] Larson, E. D., Jin, H. and Celik, F. E., Large-scale gasification-based coproduction of fuels and electricity from switchgrass. *Biofuels. Bioproducts and Biorefining*. 3 (2009) 174-194, doi: <https://doi.org/10.1002/bbb.137>.
- [49] Dunn, S. Re-Inventing The Maintenance Process. in *Queensland Maintenance Conference*. (1998).
- [50] Vianello, C., Milazzo, M.F. and Maschio, G., Cost-benefit analysis approach for the management of industrial safety in chemical and petrochemical industry. *Journal of Loss Prevention in the Process Industries*. 58 (2019) 116-123, doi: <https://doi.org/10.1016/j.jlp.2019.02.006>.
- [51] Alias, N. B., Ibrahim, N. and Hamid, M. K. A., Pyrolysis of Empty Fruit Bunch by Thermogravimetric Analysis. *Energy Procedia*. 61 (2014) 2532-2536, doi: <https://doi.org/10.1016/j.egypro.2014.12.039>.
- [52] Tan, E. C. D., Talmadge, M., Dutta, A., Hensley, J., Schaidle, J. and Biddy, M. *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons via Indirect Liquefaction. Thermochemical Research Pathway to High-Octane Gasoline Blendstock Through Methanol/Dimethyl Ether Intermediates*. Report No.

- NREL/TP-5100 - 62402, National Renewable Energy Laboratory (NREL), CO, United States, (2015) 17, doi: <https://doi.org/10.2172/1215006>.
- [53] BPS Statistics Indonesia. *Rupiah Credit Interest Rates By Group of Banks - Statistical Data*, <<https://www.bps.go.id/en/statistics-table/2/MzgZlzl=/rupiah-credit-interest-rates-by-group-of-banks.html>> (2025).
- [54] Muliahati, A., Karamah, E. F. and Kaifiah, I., Study of domestic coal-based dimethyl ether (DME) utilization to reduce LPG import. *E3S Web of Conference*. 67 (2018) 01005, doi: <https://doi.org/10.1051/e3sconf/20186701005>.
- [55] Nur, S. M. *Biomass to Bioenergy* [in Indonesian], <https://www.academia.edu/18620289/BIOMASSA_MENJADI_BIOENERGI> (2015).
- [56] Afokin, M. I. and Magomedova, M. V., Process Solutions for Recovery of Dimethyl Ether Produced Through One-Step Synthesis and Their Assessment. *Petroleum Chemistry*. 61 (2021) 115-122, doi: <https://doi.org/10.1134/S0965544121020109>.
- [57] Inokoshi, O., Ohno, Y., Ogawa, T., Inoue, N. and Tokoeda, N. A New DME Production Technology 100tons / day DME Direct Synthesis Demonstration Plant Project. in *Proceedings of the Fifteenth International Offshore and Polar Engineering Conference*. (2005) 49-53.
- [58] Matzen, M. and Demirel, Y., Methanol and dimethyl ether from renewable hydrogen and carbon dioxide: Alternative fuels production and life-cycle assessment. *Journal of Cleaner Production*. 139 (2016) 1068-1077, doi: <https://doi.org/10.1016/j.jclepro.2016.08.163>.
- [59] Ohno, Y., Yagi, H., Inoue, N., Okuyama, K. and Aoki, S. in *Studies in Surface Science and Catalysis: Slurry phase DME direct synthesis technology -100 tons/day demonstration plant operation and scale up study*. Elsevier, (2007) 403-408, doi: [https://doi.org/10.1016/S0167-2991\(07\)80165-0](https://doi.org/10.1016/S0167-2991(07)80165-0).
- [60] Kreutz, T. G., Larson, E. D., Liu, G. and Williams, R. H. Fischer-Tropsch fuels from coal and biomass. in *25th Annual International Pittsburgh Coal Conference*. (2008) 24.
- [61] Kalimantanbisnis. *Central Kalimantan's 2022 Minimum Wage, Seruyan Regency Highest - Kalimantan Bisnis.com* [in Indonesian], <<https://kalimantan.bisnis.com/read/20211202/407/1473202/umk-kalteng-2022-kabupaten-seruyan-tertinggi>> (2022).
- [62] Osorio-Tejada, J. L., Llera-Sastresa, E. and Scarpellini, S., Liquefied natural gas: Could it be a reliable option for road freight transport in the EU? *Renewable and Sustainable Energy Reviews*. 71 (2017) 785-795, doi: <https://doi.org/10.1016/j.rser.2016.12.104>.
- [63] Al Farisi, A., Zaenal and Sriyanti., The Effect of Haul Road Geometry on Fuel Consumption in Overburden Transportation at PT Pancaran Surya Abadi Coal Mining in Muara Badak, Kutai Kartanegara [in Indonesian]. *Bandung Conference Series: Mining Engineering*. 5 (2025) 53-62, doi: <https://doi.org/10.29313/bcsme.v5i1.17302>.
- [64] Semelsberger, T. A., Borup, R. L. and Greene, H. L., Dimethyl ether (DME) as an alternative fuel. *Journal of Power Sources*. 156 (2006) 497-511, doi: <https://doi.org/10.1016/j.jpowsour.2005.05.082>.
- [65] Arcoumanis, C., Bae, C., Crookes, R. and Kinoshita, E., The potential of di-methyl ether (DME) as an alternative fuel for compression-ignition engines: A review. *Fuel*. 87 (2008) 1014-1030, doi: <https://doi.org/10.1016/j.fuel.2007.06.007>.
- [66] Saepudin, A., Rachmawati, I., Kuncoro, R. H. and Angretnowati, Y., Indonesia Green Mining Industry. *European Journal of Development Studies*, 2 (2022) 22-32, doi: <http://dx.doi.org/10.24018/ejdevelop.2022.2.5.169>.
- [67] Cano, Z. P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M. and Chen, Z., Batteries and fuel cells for emerging electric vehicle markets. *Nature Energy*. 3 (2018) 279-289, doi: <https://doi.org/10.1038/s41560-018-0108-1>.
- [68] Heryadi, R., Utama, J. D. H., Hikariantara, I. P. and Saufi, M., Green Ammonia production potential prediction from Oil Palm Frond Waste in the Kalimantan Region. *IOP Conference Series: Earth and Environmental Science*. 1562 (2025) 012023, doi: <https://doi.org/10.1088/1755-1315/1562/1/012023>.
- [69] Schüth, F., Challenges in hydrogen storage. *The European Physical Journal Special Topics*. 176 (2009) 155-166, doi: <https://doi.org/10.1140/epjst/e2009-01155-x>.