PENA TEKNIK
JURNAL ILMIAH ILMU - ILMU TEKNIK

Vol. 10, No.1, March (2025)
p-ISSN 2502-8952
e-ISSN 2623-2197
https://ojs.unanda.ac.id/index.php/jiit/index

Pre-Design and Environmental Impact Analysis of Methanol Plant from Natural Gas with Dielectric Barrier Discharge Reactor

Jansen Briano [1,*], Kornelius S. Tanuwidjaja [1], Yosia G. Kurniawan [1], Meyland [1], Samuel P. Aletheia [1]

[1] *Chemical and Food Processing, Calvin Institute of Technology, Jakarta, Indonesia*
** Corresponding Author E-mail: jbriano.work@gmail.com*

Abstract

In Indonesia, the demand for methanol reaches 1.1 million tons per year, with the majority being fulfilled through imports. The formaldehyde industry is the primary consumer, using 80% of the total methanol consumption. Increasing domestic methanol production has become crucial due to dependency on imports and the presence of only one producer with a capacity of 660,000 tons per year. The preliminary design of a low-emission methanol plant is a first step toward a more environmentally friendly methanol industry in Indonesia, aiming to reduce carbon emissions and dependence on fossil fuels. Methanol production at this plant results in the lowest possible carbon emissions, using raw materials such as methane gas, purified water, and helium. The methane gas is sourced from pure liquified natural gas (LNG) from PT Badak NGL, which has been purified from CO2 and H2S under operating conditions of -162°C and 1 bar pressure. Meanwhile, the purified water is obtained through seawater desalination processes. The reaction between methane and purified water occurs in a dielectric barrier discharge (DBD) reactor at 1 bar pressure, with helium as the inert gas. The plant's production capacity reaches 500,000 tons per year, with a purity level of 99.95% and zero greenhouse gas emissions. To achieve profitability comparable to conventional methanol, a minimum methanol selling price of $970/ton is required. When the carbon credit price is $1200/tCO2, the methanol produced by this plant will be more profitable for investors compared to conventional methanol production or methanol production using carbon capture and utilization technology.

Keywords:
Dielectric Barrier Discharge (DBD); Direct Conversion; Methanol Production; Low Carbon Emission; Plasma Reactor

1. INTRODUCTION

East Kalimantan, Indonesia, stands out as a prime location for establishing chemical production facilities, particularly for liquefied natural gas (LNG) and methanol, due to its substantial gas reserves in fields such as Badak, Nilam, and Samberah. The Bontang LNG plant, one of the largest globally, has been operational since 1977 and supplies LNG to major markets like Japan, South Korea, and Taiwan. This facility's modern infrastructure, combined with its proximity to offshore reserves, makes it a reliable and strategic site for large-scale LNG production and export. East Kalimantan's location further enhances its role as a key export hub to major Asian consumers, bolstered by government support aimed at prioritizing industrial development in the region (Hydrocarbons Technology; ERIA, 2021; Indonesia Investments, 2016).

Methanol production is increasingly relevant to Indonesia's industrial and energy strategies due to rising global demand, projected to reach 500 million tons by 2050 (IRENA, 2021). Currently, Indonesia's methanol demand is around 1.1 million tons annually, with over 80% met through imports (Maulana, 2021). Methanol has extensive applications across Indonesian industries, including fuel production, chemical manufacturing, solvents, and cosmetics. Importantly, methanol as a fuel helps reduce emissions of pollutants such as carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) in combustion engines (Albana). Methanol is also integral to Indonesia's biodiesel initiatives (B30), a program that saved the country $4.54 billion in foreign exchange and cut CO_2 emissions by 25 million tons in 2021, with future plans to increase blending rates to B40 and B50 driving additional domestic demand for methanol (Ministry of Energy and Mineral Resources, 2021).

doi http://dx.doi.org/10.51557/pt_jiit.v10i1.2950
article history: Received October 24, 2024; Received in revised from March 01, 2025; Accepted March 02, 2025;
Available online March 25, 2025.

LNG serves as a cleaner alternative to coal for methanol production in East Kalimantan, supporting Indonesia's climate goals and aligning with commitments under the Paris Agreement and COP28. Utilizing LNG, alongside advanced technologies such as the Dielectric Barrier Discharge (DBD) reactor for methane-to-methanol conversion, holds potential to reduce emissions. DBD reactors operate at lower temperatures and avoid intermediate steps like syngas production, thus reducing both energy consumption and carbon emissions. This aligns with Indonesia's Nationally Determined Contributions (NDCs), underscoring the country's proactive stance in global climate action and strengthening its energy security by advancing cleaner industrial practices.

However, the use of LNG for methanol production presents notable challenges. Methane leakage, which can occur during extraction, processing, and transport, contributes to greenhouse gas emissions, offsetting some environmental benefits of LNG (Kourkoumpas et al., 2018). While technologies like the DBD reactor show promise for low-emission methanol production, maintaining optimal conditions is complex and energy-intensive, often requiring a renewable energy supply to fully realize CO_2 emissions reductions (Román-Leshkov & Dumesic, 2014). Additionally, the infrastructure needed for LNG production, storage, and transport is costly, and lapses in maintenance can exacerbate methane leakage, potentially undermining emission reduction goals (Yang et al., 2019). Addressing these challenges demands continuous innovation and robust methane management strategies to ensure that LNG-based methanol production aligns with Indonesia's climate objectives.

Methanol production from LNG not only offers a cleaner combustion profile but also allows flexibility in supply chain diversification, enhancing energy security and price stability (Yusuf, 2023). As Indonesia aims to reduce carbon emissions and transition towards cleaner energy, LNG-based methanol production could serve as a bridge to a sustainable energy future, offsetting some reliance on coal power and reducing methanol import dependency. Currently, Indonesia Kaltim Methanol Industri, the primary domestic producer, has an annual capacity of 660,000 tons, indicating potential for expansion (Parderio et al., 2022).

This research aims to design a sustainable methanol production plant in East Kalimantan, leveraging local natural gas reserves. The study will evaluate the potential of DBD technology for methanol production, simulate the production process, and analyze carbon emissions, energy consumption, and economic viability, using metrics such as NPV, IRR, and payback period. This approach supports Indonesia's economic growth and climate commitments by advancing cleaner methanol production methods. Additionally, it aims to reduce reliance on methanol imports, bolstering key industries like biodiesel and chemical manufacturing while contributing to environmental sustainability.

2. RESEARCH METHODS

This study aims to analyze the feasibility of producing methanol directly from methane using a plasma-based conversion method. The research methodology includes a comprehensive literature review, process modeling and simulation, and an economic analysis to evaluate both the technical and financial viability of this production approach. By investigating key factors such as reaction mechanisms, process efficiency, and economic performance, this research contributes valuable insights into the potential for more sustainable and efficient methanol production technologies.

2.1 Literature Review

This literature review establishes the foundation for understanding the complex dynamics of direct methane-to-methanol conversion through plasma technology. In examining past research, emphasis was placed on identifying parameters critical to simulating this conversion and on addressing challenges inherent in the process. The review spans multiple areas, including reaction mechanisms, catalyst performance, plasma technology, separation techniques, and equipment design, to provide a comprehensive understanding of this emerging approach to methanol production.

Traditionally, methanol production has relied on syngas—a mixture of hydrogen (H_2) and carbon dioxide (CO_2) generated through the gasification of raw materials such as coal or biomass. This conventional method is energy-intensive and produces significant CO_2 emissions, which has led to the exploration of alternative feedstock and technologies that incorporate carbon capture or utilize H_2 generated via renewable-powered electrolysis. Despite these adaptations, methanol production via syngas remains energy-demanding, prompting recent studies to investigate direct methane-to-methanol conversion as a more energy-efficient approach.

Table 1 below compares conventional methanol production reactions with those involved in direct methane-to-methanol conversion. It is evident from these reactions that the energy required in conventional processes is generally higher due to the endothermic nature of the first step, highlighting a potential advantage of direct conversion methods in energy savings.

Table 1. Methanol Process Reactions (Al-Rowaili et al., 2022; Pröll & Lyngfelt, 2022; Li et al., 2021)

Conventional Methanol Production Reactions	**Direct Methane to Methanol Production Reactions**
$CH_4(g) + H_2O(g) \leftrightharpoons CO(g) + 3H_2(g)$ ($\Delta H_{298}K$ = +206 kJ/mol)	$CH_4 + 1/2O_2 \leftrightharpoons CH_3OH(g)$ ($\Delta H_{298}K$ = -126 kJ/mol)
$CO(g) + H_2O(g) \leftrightharpoons CO_2(g) + H_2(g)$ ($\Delta H_{298}K$ = -41 kJ/mol)	$CH_4 + H_2O \leftrightharpoons CH_3OH + H\cdot$
$CH_4(g) + 2H_2O(g) \leftrightharpoons CO_2(g) + 4H_2(g)$ ($\Delta H_{298}K$ = +165 kJ/mol)	$CH_4 + N_2O \rightarrow CH_3OH + N_2$ ($\Delta H_{298}K$ = -159.0 kJ/mol)
CO2(g) + $3H_2(g) \leftrightharpoons CH_3OH(g) + H_2O(g)$ ($\Delta H_{298}K$ = -49,16 kJ/mol)	
$CO(g) + 2H_2(g) \leftrightharpoons CH_3OH(g)$ ($\Delta H_{298}K$ = -90,64 kJ/mol)	

One of the primary challenges in the direct conversion of methane to methanol lies in the thermodynamics. This process typically demands more energy to activate methane than is required to convert methanol to CO or CO_2, which has spurred research into low-energy and low-temperature conversion methods. Plasma-assisted conversion, particularly with Dielectric Barrier Discharge (DBD) reactors, emerges as a promising solution, as it provides the necessary energy to facilitate reactions under milder conditions than conventional thermal processes. Plasma reactors are advantageous in handling methane's high activation energy while minimizing methanol over-oxidation at high temperatures.

The role of catalysts and reactant compositions is also critical for optimizing conversion efficiency and reducing byproducts. Studies by Zakaria (2016) and Nandy (2022) underscore the importance of selectivity and efficiency in methane oxidation, while Li (2023) addresses the temperature sensitivity of methane as a key bottleneck in this process. Consequently, this study adopts a low-temperature plasma reactor to address these issues, aiming to enhance selectivity and reduce over-oxidation in methanol production.

A promising approach is the use of a non-thermal plasma reactor, particularly one utilizing DBD technology. Most prior studies have been limited to small-scale experiments, motivating this study to evaluate DBD performance on an industrial scale using DWSim simulation software. DWSim is selected for its open-source nature, making it accessible for academic research without the licensing fees associated with proprietary tools like Aspen Plus and CHEMCAD. Its accuracy in gas-phase reaction simulations has been validated in studies by Subramanian (2023) and Andreasen (2022) for applications such as hydrogen production and gas plant simulations. While DWSim does lack a developed library for plasma-specific reactions and cannot simulate plasma properties or radical ions—limitations that commercial software may overcome—it remains a versatile, cost-effective option for simulating heat exchangers, separation units, and reactors. Additionally, copper electrodes, known to enhance plasma production and conversion efficiency, are incorporated into this reactor design.

Tables 2 and 3 list the inlet flow and reactor operating conditions assumed in this study, informed by prior research including Bi et al., to provide a baseline for simulation.

Table 2. Inlet Conditions of DWSim Parameters

Flow	Temperature (°C)	Flow Rate (kg/h)	Pressure (bar)	Composition (mol fraction)
LNG	-162	40.000	1	C_1=0,88; C_2=0,04; C_4=0,015; *i*-C_4=0,02; N_2=0,03
Helium	70	75.000	150	He=1
Demin water	25	60.000	1	H_2O=1
Boiler Feed water	25	69.692	1	H_2O=1

Table 3. Reactor Inlet and Outlet Conditions

Flow	Temperature (°C)	Flow Rate (kg/h)	Pressure (bar)	Composition (mol fraction)
Inlet	23,6339	175.000	1	C_1=0,0772; C_2=0,0035; C_3=0,0013; C_4=0,0013; *i*-C_4=0,0017; N_2=0,0026; He=0,7746; H_2O=0,1377
Outlet	100	175.000	1	C_2=0,0035; C_3=0,0013; C_4=0,0013; *i*-C_4=0,0017; N_2=0,0026; CH_3OH=0,077; He=0,7746; H_2=0,0772; H_2O=0,0605

The reaction conduct in this production is adapted from (Bi, et al.) with the reaction mechanism as shown in Figure 1 below.

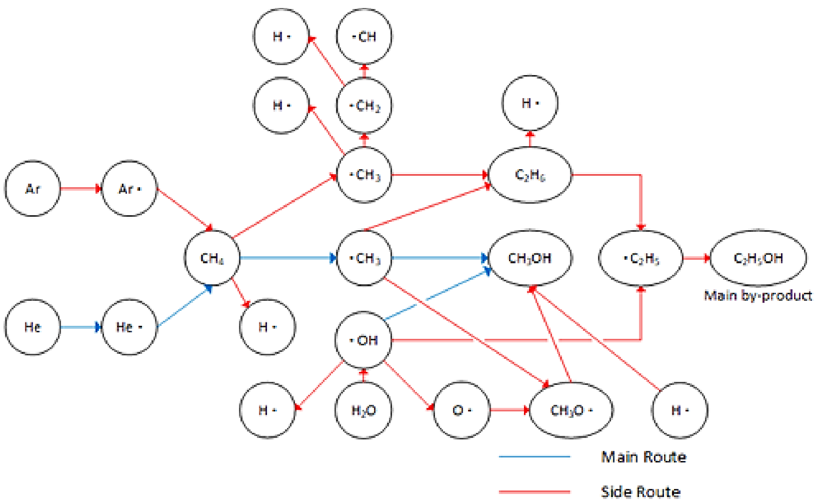

Figure 1. Direct Methane to Methanol Reaction Mechanism

Figure 1 illustrates the direct methane-to-methanol reaction mechanism within a DBD plasma reactor, adapted from prior studies. The figure details the primary (blue) and side (red) pathways involved in transforming methane (CH_4) into methanol (CH_3OH) and other byproducts. In the primary reaction, noble gas helium produces methyl radicals ($CH_3\cdot$) and hydrogen radicals (H·) when methane interacts with ionized helium plasma (He·). Simultaneously, water molecules dissociate into hydroxyl (OH·) and hydrogen radicals (H·) with the assistance of a TiO_2 catalyst. These methyl radicals react with hydroxyl radicals to form methanol, while byproducts like CH_2, CH radicals, and ethyl radicals (C_2H_5) may lead to ethanol formation. Additionally, a secondary pathway enables methanol formation through reactions between hydrogen and methoxy radicals.

Further research by Bi et al. highlights how argon (Ar) gas can increase electron density in the reactor, enhancing methane activation and the formation of methyl radicals. However, helium (He), which produces higher-energy electrons, achieves greater selectivity and reduces energy requirements. Therefore, this study utilizes a 2:1 He:CH_4 ratio to maximize methanol selectivity and streamline the separation process by minimizing byproducts.

This investigation's focus on plasma-assisted, single-step methane-to-methanol conversion, underpinned by DBD technology and modeled in DWSim, provides a pathway for industrial-scale applications that could mitigate environmental impacts and improve energy efficiency in methanol production.

This leads us to the primary reaction outlined below, which occurs in both the plasma and liquid phases, resulting in plasma being produced at the plasma interface once the reaction is complete.

$$CH_4 + H_2O \rightarrow CH_3OH + 2H \cdot$$

2.2 Process and Plant Overview

The methanol production process consists of three key stages: raw material preparation, methanol synthesis, and product purification. Initially, raw materials—including methane sourced from liquefied natural gas (LNG) and high-purity water—undergo preparatory steps to reach optimal conditions for reaction. Methanol synthesis occurs in a Dielectric Barrier Discharge (DBD) reactor, where helium is utilized as an inert gas to enhance reaction efficiency. The final stage involves product purification, where a series of separation and distillation steps ensure the methanol meets the AA-grade quality standard, as depicted in Figure 2, the process flow diagram for this design.

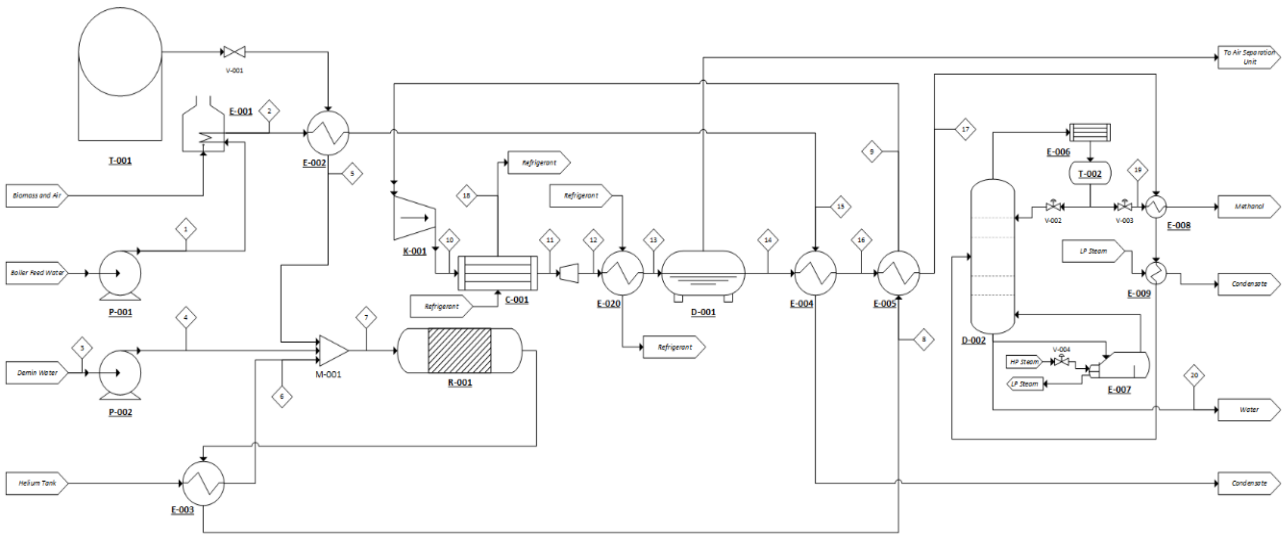

Figure 2. Direct Methane to Methanol Process Flow Diagram

2.2.1 Raw Material Preparation Stage

In the raw material preparation stage, LNG with a methane purity of at least 95% is the primary feedstock. Initially stored at -162°C and 1 bar, the LNG is heated to 300°C and pressurized to 6 bar using high-pressure steam. Helium is introduced at double the molar flow rate of methane, acting as an inert gas to achieve a higher selectivity, as stated by Bi et al. (2019). Water, another essential input, is provided in a high-purity form obtained through seawater desalination using seawater reverse osmosis (SWRO).

2.2.2 Methanol Formation Reaction Stage

Methanol synthesis occurs in the DBD reactor through a plasma-assisted reaction between methane and water. Helium is introduced to generate plasma when an electric current is applied across the reactor's electrodes. This plasma excites helium atoms, facilitating their interaction with methane and water, which enhances methanol production at lower temperatures and atmospheric pressure compared to conventional thermal methods. Plasma technology not only improves reaction efficiency but also reduces emissions. Bi et al. (2019) demonstrated that a helium-to-methane ratio of 2:1 provides optimal selectivity, which would otherwise decrease sharply in the absence of plasma or helium. Operating conditions are set at 27°C and 1 bar, with a residence time of 1-2 hours to maximize conversion.

2.2.3 Separation Stage

Following synthesis, the gas mixture is cooled to condense methanol, which is then separated from helium using a horizontal separator (D-001). The separated helium is recycled back to the reactor for reuse, while the condensed methanol undergoes further purification. A distillation column (D-002) purifies methanol to a final concentration of 99.85%, meeting AA-grade standards. Before distillation, heat exchangers (E-003, E-005) cool the methanol to facilitate condensation, after which the product is reheated and fed into D-002 for final purification.

2.3 Process Modelling and Simulation

The methanol production plant's mass and energy balances were modeled using DWSim, an open-source chemical process simulator recognized for its application across various fields, including hydrogen production, refrigeration system optimization, and oil and gas plant modeling (Subramanian, 2023; Chantasiriwan, 2023; Andreasen, 2022). DWSim's versatility and wide-ranging applicability made it an ideal choice for this study.

In the simulation, critical parameters such as mass flow rates, temperatures, pressures, and energy consumption were integrated, along with assumptions on LNG purity and plasma efficiency to realistically replicate the production process. This modeling effort provided insights into both the technical feasibility and environmental impact of the plant's operation.

The recent focus on direct methane-to-methanol conversion has underscored the importance of selectivity and efficiency in such processes. Zakaria (2016) reviewed various conversion methods, while Nandy (2022) studied catalysts that support high-selectivity methane oxidation. Li (2023) identified selectivity challenges at high temperatures, which often result in methanol transforming into other derivatives. In response, this study employs a low-temperature plasma reactor to optimize selectivity and maintain methanol as the primary product.

LNG with a minimum methane purity of 95% is used as the primary material, initially at -162°C and 1 bar. It's heated to 300°C and 6 bar using high-pressure steam. Helium, introduced at double the methane molar flow rate. Followed by high-purity water is supplied via seawater desalination through SWRO.

2.4 Economic Analysis

Evaluating the economic feasibility of the low-emission methanol production plant is critical to understanding its potential profitability. Key financial metrics, such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP), and Return on Investment (ROI), were calculated to assess the plant's financial performance.

The plant's total capital expenditure (CAPEX) is estimated at $479.68 million, with annual operating expenses (OPEX) projected at $343.65 million, as outlined in Table 5. These CAPEX and OPEX estimates were calculated using multiplication factors based on Garret (2013). With projected annual revenue of $70.64 million, the plant's net present value (NPV) is calculated at $171.67 million, and the internal rate of return (IRR) stands at 15.38%, resulting in a payback period of approximately 6.79 years. These financial indicators suggest that, although the plant offers a reasonable return on investment, its profitability remains highly sensitive to fluctuations in methanol prices and carbon credit values.

Table 4. Total Capital Expenditure

Component	**Cost (US$)**
Equipment	61,929,557
Site Development	146,153,756
Land and Building	24,771,823
Other	23,285,514
Start-Up	13,971,308
Working Capital	34,928,270
Contractor and Contingency	174,641,352
Total Capital	479,681,580

Table 5. Total Operational Expenditure Calculation without Equity and Depreciation

Component	**Cost/year (US$)**
Raw materials, additives, catalysts	199,000,042
Power generation utility	4,644,689
Operational labor and labor-related costs	28,357
Capital related costs	57,817,930
Sales related costs	82,160,517
Total Operational Per Year	343,651,536

We calculated key financial metrics, including Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP), and Return on Investment (ROI). NPV indicates the value of the project and is used in capital budgeting and investment planning to assess the profitability of the projected investment (Lin and Nagalingam, 2000). Meanwhile, IRR is used to demonstrate the attractiveness of a project and estimate its potential for generating profits. ROI is used to measure the efficiency or profitability of an investment. The Payback Period shows the time required for an investment to return an amount equivalent to the initial investment (Park, 2007). The economic analysis calculations are based on the formulas listed in equations (1), (2), and (3).

$$NPV = \sum_{n=1}^{n=T} \frac{CF_n}{1+i^n} - TCI \qquad (1)$$

$$PB = FC + \frac{I}{P+D} \qquad (2)$$

$$ROI = \frac{C}{TCI} * 100\% \qquad (3)$$

Where CF_n represents the net cash flow during period T, while TCI refers to the total capital investment. The discount rate is denoted by *i*, and T indicates the number of time periods. FC refers to the depreciable fixed capital investment, *i* stands for the interest on TCI over the projected service life, P represents the average annual profit, D denotes the average annual depreciation, and C is the annual net profit after taxes. The economic analysis was conducted using Microsoft Excel.

The results of the economic and profitability analysis will provide a comprehensive understanding of the potential economic benefits and risks associated with the operation of this plant. To achieve this, several parameters were considered as follows:

1. The plant will be constructed at the beginning of 2024 and will begin operations in early 2025.
2. Low-emission methanol production will commence in early 2026, with a lifespan of 15 years.
3. Some equipment will have salvage value at the end of its service life.
4. A tax rate of 22% (PwC, 2023).

5. Depreciation is 10% for major equipment and 3% for support equipment and buildings, using the straight-line method (Ministry of Finance, 2023).

Total capital investment encompasses both fixed and working capital, covering all process equipment and auxiliary components. Fixed capital is categorized into direct costs, which are directly related to production, and indirect costs, which are not easily linked to a specific production activity. Working capital accounts for costs such as initial production expenses and inventory costs for raw materials and other supplies. These cost estimations are derived from the indexed time of plant establishment, using the bare module factor as outlined by Seider et al. (2004).

3. RESULT AND DISCUSSION

3.1 Plant Performance and Environmental Analysis

The simulation results from DWSim V8.7.1 were analyzed and scaled up to an industrial level, as illustrated in the process flow diagram (Figure 3). The methanol production process encompasses LNG preheating, reaction, separation, and purification stages. Initially, LNG is preheated from -162°C to 80°C, while water is maintained at 25°C. Helium, used as an inert gas, is then introduced before the mixture enters the reactor at 27°C. The reaction proceeds at a pressure of 1 bar and a temperature of 27°C, with 66 MW/day of electrical energy used to convert methane into methanol via helium plasma. The plasma provides energy that significantly enhances the reaction selectivity, achieving a conversion selectivity of 93% by facilitating efficient methane-to-methanol conversion at lower temperatures. Steam, generated from the combustion of palm shell biomass, provides 6.015 MW/day of the required process energy.

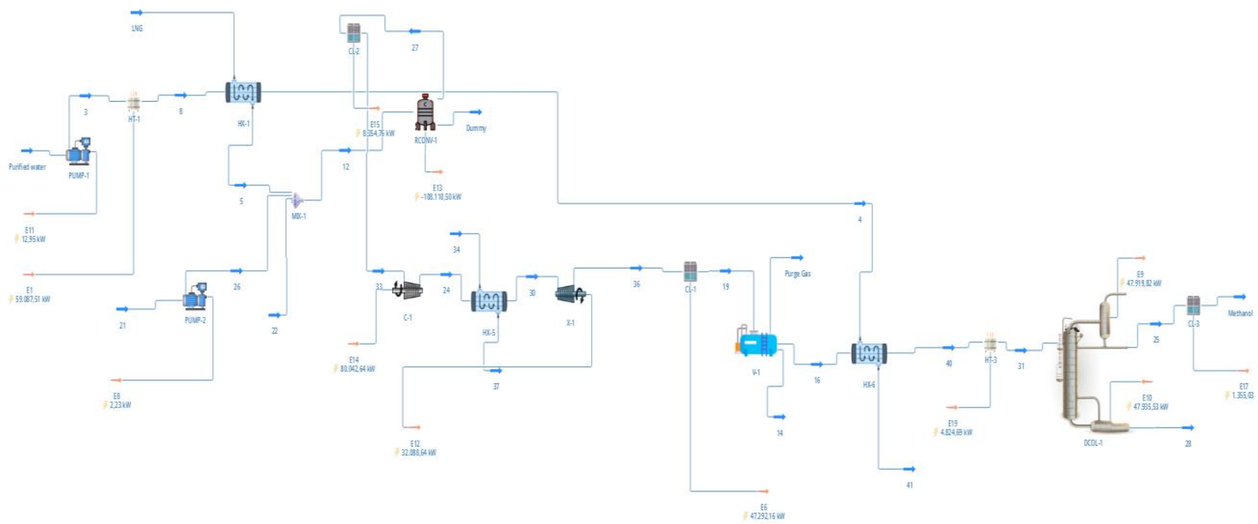

Figure 3. DWSim Simulation Process Flow Diagram

Environmental considerations are integral to the plant design, which emphasizes reduced emissions throughout LNG-based methanol production. During the upstream stage (extraction and processing), CO2 and CH4 emissions occur, particularly in regions with lenient flaring and venting regulations. Midstream processes (liquefaction and transport) are energy-intensive, generating CO2 emissions and potentially releasing CH4 through leaks in infrastructure. In the downstream stage (regasification and combustion), CO2 emissions dominate, although CH4 leaks may persist due to inadequate maintenance.

To address these environmental challenges, renewable energy sources are used to power the plasma generation system, significantly reducing the plant's carbon footprint. Additionally, a carbon capture system utilizing diethanolamine (DEA) captures up to 99.9% of CO2 emissions, which are subsequently repurposed for secondary processes. This method not only supports the production of blue methanol but also aligns with sustainable industrial practices by minimizing greenhouse gas emissions. Key performance indicators demonstrate that the integration of renewable energy and carbon capture technologies substantially enhances the environmental performance of the process.

However, economic analysis indicates that the financial viability of low-emission methanol production is sensitive to methanol market prices and carbon credit policies. For the plant to remain competitive with traditional methods, methanol prices must reach $970 per ton. The introduction of carbon credits could improve economic outcomes, particularly as stricter CO_2 emission penalties are expected in the future.

3.2 Comparative Analysis

While Bi (2019) achieves a conversion selectivity of 93%, recent studies conducted by Huan (2024) report a significantly lower selectivity of 51%, highlighting the variability in performance across different studies. Comparatively, the industrial application of dielectric barrier discharge (DBD) reactors for chemical production remains underexplored, underscoring challenges in demonstrating the economic feasibility of such systems. Although this innovative approach shows potential advantages, such as the possibility of substituting helium with more accessible inert gases or enhancing recycling mechanisms to reduce operational costs, technologies like DBD reactors face significant economic hurdles. For instance, methane-to-methanol conversion using DBD reactors suffers from high energy consumption, extended payback periods, and lower internal rates of return (IRR) compared to conventional methods (Rahimpour et al., 2014; Rahimi et al., 2020). Further optimization is required to improve yields and reduce costs, making these systems less competitive overall.

3.3 Industrial Scalability and Challenges

Scaling this technology to industrial levels involves addressing several challenges, including resource limitations and infrastructure requirements. Helium dependency represents a critical barrier due to its limited global availability and high cost, which is exacerbated by the need for specialized storage and processing infrastructure. These challenges are particularly pronounced in regions like Indonesia, where helium resources and processing capabilities are limited.

Additionally, regulatory frameworks governing carbon credits and emissions play a pivotal role in determining project feasibility. Although current carbon credit prices in Indonesia are relatively low, stricter environmental policies and higher carbon penalty thresholds could improve the economic competitiveness of low-emission methanol production. Moreover, logistical challenges related to LNG handling and biomass combustion require strategic planning to ensure reliable and cost-effective operations.

Despite these obstacles, the plant's reliance on renewable energy sources and its robust carbon capture system positions it as a sustainable alternative to traditional methanol production. However, further studies are needed to evaluate long-term economic impacts, including equipment degradation and fluctuating carbon credit prices, to enhance scalability and cost-effectiveness.

3.4 Economic and Sensitivity Analysis

The economic analysis was calculated using a spreadsheet. The prices of equipment, piping, instrumentation, and buildings were estimated using sizing and price factors from Turton et al. (Turton, 2018). The plant's operating costs were assumed to be a percentage of the investment cost based on Park et al. (Park, 2007). Meanwhile, profitability analyses such as NPV, IRR, PB, and ROI used the equations explained in the previous section for 15 years. A summary of the plant's economic calculation results and profitability analysis is presented in Table 6.

Table 6. Economic Analysis of Low Methanol Emissions from Natural Gas

CAPEX (US$)	479,681,580

OPEX (US$/year)	343,651,536
Revenue US$/year)	70,635,332
NPV (US$)	171,679,332
IRR	15.38%
PBP (years)	6.79
ROI	13.13%

**All financial data are presented in U.S. Dollars (USD) for consistency. Original calculations were conducted in Indonesian Rupiah (IDR) and converted at an exchange rate of IDR 15,774 per USD, effective as of November 7, 2024.*

The economic analysis of the proposed methanol production project shows strong profitability, with an ROI of 13.13%, an IRR of 15.38%, and an NPV of $171.68 million, exceeding the initial investment. The payback period is just 6.79 years, making the project financially attractive (Brockway et al., 2019).

Other studies also support the feasibility of natural gas-based methanol production. For example, one study using an adiabatic pre-reformer reactor model in Aspen HYSYS V10 reported an IRR of 11.73% and an NPV of $166.63 million (Aletheia & Meyland, 2024). Another study on hybrid steam reforming of glycerol and natural gas confirmed its economic viability (Balegedde Ramachandran et al., 2013).

The economic viability of producing low-emission methanol from LNG is promising but highly dependent on market conditions. As shown in the sensitivity analysis, achieving profitability comparable to conventional methods requires a methanol price of at least $970 per ton to offset the higher operational costs of low-emission technologies.

Figure 4. Methanol Price per Ton over IRR

Carbon credit pricing is also a critical factor in determining financial performance. While current carbon credit market incentives remain limited, the profitability of low-emission methanol production improves as carbon credit prices rise. For example, at a carbon credit price of $160/tCO_2$, low-emission methanol becomes competitive with gray methanol. However, a carbon price of $1,200/tCO_2$ is required for low-emission methanol to surpass blue methanol in terms of profitability. Sensitivity analyses on CO_2 emission penalties highlight the importance of aligning economic incentives with environmental objectives to sustain long-term profitability.

3.4.1 Levelized Cost of Methanol (LCOM)

The levelized cost of methanol (LCOM) represents the selling price of methanol required to achieve attractive profits relative to its production costs, as formulated by Martin et al (2024).

Table 7 below compares methanol production across three different schemes: gray, blue, and low-emission methanol. Gray methanol, as outlined by IRENA (2021), generates CO_2 emissions without any further treatment. In contrast, blue methanol captures and processes 90% of CO_2 emissions through a carbon capture, utilization, and storage (CCUS) system. Finally, the production of low-emission methanol focuses on minimizing emissions through improved processes.

Table 7. CO_2 emissions from various types of process

	Gray Methanol	*Blue Methanol*	This Study
Total CO_2 emissions from methanol production (tCO_{2e}/tMeOH)	3,10	0,31 (90% captured)	0
LCOM ($/MeOH)	490	598,81	970

To understand the cost and feasibility of producing methanol sustainably, it's essential to compare three key types: gray, blue, and green methanol. Gray methanol, produced using conventional fossil fuels, has the highest carbon footprint but remains the most cost-effective option. Blue methanol incorporates carbon capture, utilization, and storage (CCUS) technologies, which reduce emissions by capturing CO2 from production processes, potentially allowing blue methanol to be produced at a levelized cost of approximately $598 per metric ton. Green methanol, derived from renewable sources like biomass or through the electrolysis of water powered by renewable energy, is the least polluting but also the most costly, with a production cost target of around $970 per metric ton to achieve comparable profitability to gray methanol.

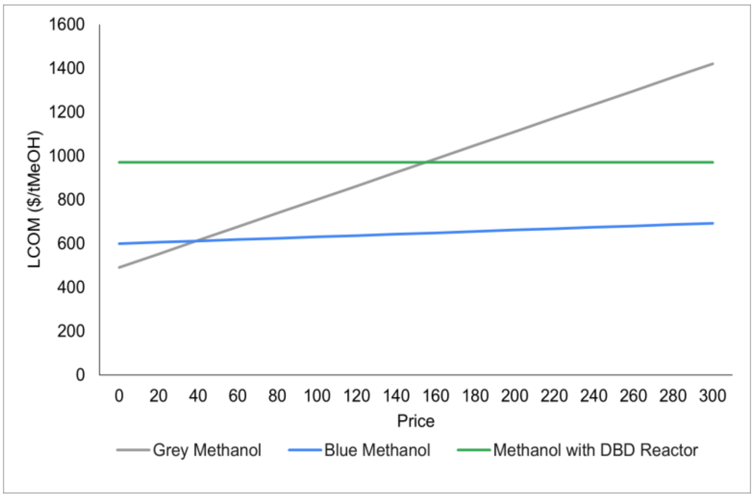

Figure 5. Effect of Levelized Cost of Methanol on Carbon Taxes

Figure 5 illustrates the effect of varying carbon credit prices on methanol profitability, showing that when carbon credits reach $39 per ton of CO_2, blue methanol becomes more profitable than gray methanol. Green methanol would require a higher credit price of $160 per ton of CO_2 to surpass gray methanol, and an exceptional credit value of $1200 per ton of CO_2 to outcompete blue methanol.

The profitability challenge of green methanol is compounded by its higher production costs. By integrating carbon credit incentives, however, the financial gap can be narrowed. With current carbon credits valued at roughly $4.5 per ton of CO_2 in Indonesia (Indonesia Opens Carbon Trading Market to Both Skepticism and Hope, 2023), the carbon market could play a pivotal role in enhancing the competitiveness of low-emission methanol.

Thus, while green methanol holds potential for future profitability in a stricter regulatory environment, current carbon credit levels make it economically challenging to exceed blue methanol's profitability. This analysis underscores the need for further policy support to make sustainable methanol solutions financially viable in the long term.

3.4.2 Levelized Cost of Electricity (LCOE)

The Levelized Cost of Electricity (LCOE) is a method used to calculate the average cost of electricity generated by an asset over its operational lifetime. This metric is commonly used to compare electricity costs across various energy sources or projects, providing a standardized framework for evaluation. Simply put, LCOE represents the cost per unit of electricity produced over the lifetime of a generating asset (Levelized Cost of Energy (LCOE), 2024).

In the context of the methanol plant, LCOE calculations are essential for evaluating potential cost savings related to both process and non-process energy usage. Given the plant's reliance on energy-intensive equipment such as pumps, compressors, and plasma reactors, determining the LCOE of the electricity supply is critical for assessing the efficiency of the designed power generation system. Based on the analysis, the LCOE for this plant is calculated to be Rp 723,517,318 per megawatt (MW) per year.

4. CONCLUSIONS

This study presents the design of a methanol production plant with a capacity of 500,000 tons per year, utilizing natural gas as the primary feedstock. The process involves natural gas purification, a direct methane-to-methanol conversion using a Dielectric Barrier Discharge (DBD) reactor, and subsequent methanol separation and purification. The simulation results confirm that the process can produce methanol with AA-grade purity while significantly reducing carbon emissions.

From an economic perspective, the plant demonstrates profitability with an IRR of 15.38% and a payback period of 6.79 years, making it a viable investment under current market conditions. However, profitability remains sensitive to methanol prices and carbon credits, highlighting the need for supportive environmental policies. Overall, this study provides a foundation for sustainable methanol production and contributes to Indonesia's efforts to achieve self-sufficiency in chemical production while reducing environmental impact.

The simulation modeled using DWSim demonstrates that this process can produce methanol with AA grade quality. From an economic perspective, financial analysis indicates that investment in this plant is profitable, with an IRR of 15.38%, a payback period of 6.79 years, and an ROI of 13.13%. Therefore, this plant can be considered a viable project to support government policies related to low-emission plants. Overall, this design provides a foundation for the implementation of a sustainable and economical methanol production plant from natural gas and contributes to efforts to achieve chemical production self-sufficiency and national environmental targets.

5. ACKNOWLEDGMENTS

We would like to express our gratitude to our colleagues at the Calvin Institute of Technology who supported the authors in conducting this research study

6. REFERENCES

Al-Rowaili, F. N., Khalafalla, S. S., Al-Yami, D. S., Jamal, A., Ahmed, U., Zahid, U., & Al-Mutairi, E. M. (2022). Techno-economic evaluation of methanol production via gasification of vacuum residue and conventional reforming routes. *Chemical Engineering Research and Design*, *177*, 365–375. https://doi.org/10.1016/j.cherd.2021.11.004

Aletheia, S. P., & Meyland, M. (2024a). Techno-economic analysis of blue methanol production from natural gas with carbon capture in Indonesia. *International Journal of Engineering Continuity*, *3*(2), 54–68. https://doi.org/10.58291/ijec.v3i2.288

Andreasen, A. (2022). *Evaluation of an Open-source Chemical Process Simulator Using a Plant-wide Oil and Gas Separation Plant Flowsheet Model as Basis. Periodica Polytechnica Chemical Engineering, 66(3), 503–511. https://doi.org/10.3311/ppch.19678*

Badan Pusat Statistik. (n.d.). Kaltim.bps.go.id. https://kaltim.bps.go.id/indicator/6/310/1/upah-minimum-regional.html

Balegedde Ramachandran, R. P., Oudenhoven, S. R., Kersten, S. R., van Rossum, G., & van der Ham, A. G. (2013). Techno-economic analysis of biomethanol production via hybrid steam reforming of glycerol with natural gas. *Energy & Fuels*, *27*(10), 5962–5974. https://doi.org/10.1021/ef401323w

Bi, W., Tang, Y., Li, X., Dai, C., Song, C., Guo, X., & Ma, X. (2022). One-step direct conversion of methane to methanol with water in non-thermal plasma. *Communications Chemistry*, *5*(1), 1–6. https://doi.org/10.1038/s42004-022-00735-y

Chantasiriwan, S. (2023). Simulation and Optimization of Vapor Absorption Refrigeration System Using Dwsim. *Chemical Engineering Transactions*, *100*, 613-618. https://doi.org/10.3303/CET23100103

ERIA (2021), 'Outlook of LNG Production', in Kimura, S., et al. (eds.), Feasible Solutions to Deliver LNG to Midsized and Large Islands in Indonesia. ERIA Research Project Report FY2020 no.18, Jakarta: ERIA, pp.31-35.

IEA (International Energy Agency). 2021. *Methanol Production and Its Role in a Clean Energy Transition.* International Energy Agency, Paris.

IRENA – International Renewable Energy Agency. (2021). Www.irena.org. http://www.irena.org/publications

Isaac, J. (2023, December 4). *Indonesia secures climate collaborations at COP28, inking milestone agreements | Lobby - Indonesia Business Post*. Indonesia Business Post. https://indonesiabusinesspost.com/lobby/indonesia-secures-climate-collaborations-at-cop28-inking-milestone-agreements/

Jong, H. N. (2023, October 12). *Indonesia opens carbon trading market to both skepticism and hope*. Mongabay Environmental News. https://news.mongabay.com/2023/10/indonesia-opens-carbon-trading-market-to-both-skepticism-and-hope/#:~:text=Each%20metric%20ton%20of%20carbon

Kourkoumpas, D. S., Papadimou, C. D., Karellas, S., Leontaritis, A. D., Panopoulos, K. D., & Kakaras, E. (2018). A review of methanol production from biomass. *Energies*, 11(5), 1-27. https://doi.org/10.3390/en11051125

Levelized cost of energy (LCOE). Corporate Finance Institute. (2024, January 12). https://corporatefinanceinstitute.com/resources/valuation/levelized-cost-of-energy-lcoe/

Li, S., Ahmed, R., Yi, Y., & Annemie Bogaerts. (2021). Methane to Methanol through Heterogeneous Catalysis and Plasma Catalysis. *Catalysts*, *11*(5), 590–590. https://doi.org/10.3390/catal11050590

Li, Z., Chen, Y., Xie, Z., Song, W., Liu, B., & Zhao, Z. (2023). Rational Design of the Catalysts for the Direct Conversion of Methane to Methanol Based on a Descriptor Approach. *Catalysts*, *13*(8), 1226. https://doi.org/10.3390/catal13081226

Lin, G. C. I., & Nagalingam, S. V. (2000). *CIM justification and optimisation*. Taylor & Francis.

Marcel Ginu Popa, Niculae Negurescu, Pana, C., & Alexandru Racovitza. (2001). Results Obtained by Methanol Fuelling Diesel Engine. *SAE Technical Paper Series*. https://doi.org/10.4271/2001-01-3748

Martin, J. A., Tan, E. C. D., Ruddy, D. A., King, J., & To, A. T. (2024). *Temperature−Pressure Swing Process for Reactive Carbon Capture and Conversion to Methanol: Techno-Economic Analysis and Life Cycle Assessment* (NREL Report No. 88329). National Renewable Energy Laboratory.

Maulana, M. R. (2021, February 5). *Daya Pacu Industri Metanol*. Bisnis.com. https://ekonomi.bisnis.com/read/20210205/44/1352775/daya-pacu-industri-metanol

Menteri Keuangan. (2023). *PERATURAN MENTERI KEUANGAN REPUBLIK INDONESIA NOMOR 72 TAHUN 2023 1–76*. (Original work published 2023)

Nandy, A., Duan, C., Goffinet, C., & Kulik, H. J. (2022). New Strategies for Direct Methane-to-Methanol Conversion from Active Learning Exploration of 16 Million Catalysts. *JACS Au*, *2*(5), 1200–1213. https://doi.org/10.1021/jacsau.2c00176

Parderio, P. T., Dharmawan, A. D., Wibawa, G., & Wiguno, A. (2022). Pra Desain Pabrik Metanol dari Gas Alam. *Jurnal Teknik ITS*, *11*(3). https://doi.org/10.12962/j23373539.v11i3.98722

Park, C. S. (2007). *Contemporary engineering economics*. Prentice Hall.

Pröll, T., & Lyngfelt, A. (2022). Steam Methane Reforming with Chemical-Looping Combustion: Scaling of Fluidized-Bed-Heated Reformer Tubes. *Energy & Fuels*, *36*(17). https://doi.org/10.1021/acs.energyfuels.2c01086

PwC. (2023). *Indonesia Pocket Tax Book 2023*. (Original work published 2023)

R. Turton, J. Shaeiwitz, D. Bhattacharyya, W. Whiting, Analysis, Synthesis, and Design of Chemical Processes, 5 ed. Pearson Publishing, 2018.

Román-Leshkov, Y., & Dumesic, J. A. (2014). Catalysis for renewable fuel production from biomass-derived carbohydrates. *Nature Chemistry*, 6(10), 801-813. https://doi.org/10.1038/nchem.2042

Seider, W., Seader, J., Lewin, D., 2004. Product and process design principles: synthesis, analysis, and evaluation.

Subramanian, G., & Neelameggham, N. R. (2023). Process Simulation for Low Emission Hydrogen Production Using DWSIM. *the Minerals, Metals & Materials Series*, 1144–1154. https://doi.org/10.1007/978-3-031-22524-6_107

Suseno, T., & Umar, D. F. (2021). Prospect of coal-based methanol market in Indonesia. *IOP Conference Series: Earth and Environmental Science*, *882*(1), 012073. https://doi.org/10.1088/1755-1315/882/1/012073

Yang, S., Liang, B., & Feng, L. (2019). Comparative life cycle assessment of methanol and conventional fuels: Implications for greenhouse gas emissions. *Journal of Cleaner Production*, 206, 172-183. https://doi.org/10.1016/j.jclepro.2018.09.108

Yusuf, N., & Tareq Al-Ansari. (2023). Current and Future Role of Natural Gas Supply Chains in the Transition to a Low-Carbon Hydrogen Economy: A Comprehensive Review on Integrated Natural Gas Supply Chain Optimisation Models. *Energies*, *16*(22), 7672–7672. https://doi.org/10.3390/en16227672

Zakaria, Z., & Kamarudin, S. K. (2016). Direct conversion technologies of methane to methanol: An overview. *Renewable and Sustainable Energy Reviews*, *65*, 250–261. https://doi.org/10.1016/j.rser.2016.05.082

Zheng, J., Ye, J., Ortuño, M. Á., Fulton, J. L., Gutiérrez, O. Y., Camaioni, D. M., Radha Kishan Motkuri, Li, Z., Webber, T., B. Layla Mehdi, Browning, N. D., R. Lee Penn, Farha, O. K., Hupp, J. T., Truhlar, D. G., Cramer, C. J., & Lercher, J. A. (2019). Selective Methane Oxidation to Methanol on Cu-Oxo Dimers Stabilized by Zirconia Nodes of an NU-1000 Metal–Organic Framework. *Journal of the American Chemical Society*, *141*(23), 9292–9304. https://doi.org/10.1021/jacs.9b02902