Techno-Economic Analysis of Blue Methanol Production from Natural Gas with Carbon Capture in Indonesia

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Abstract: Methanol market in Indonesia is projected to grow with Compound Annual Growth Rate of 3.2% by 2034. Utilizing natural gas as a feedstock and employing carbon capture and storage technology using activated metildietanolamin with piperazine (MDEA-PZ), the process is designed to produce methanol with a low carbon footprint. The process design and simulation were carried out using Aspen HYSYS, focusing on mass and energy balances across pre-treatment, syngas formation, methanol synthesis, purification and carbon capture stages. The pilot-scale plant with a capacity of 100,000 tons per year located in the Special Economic Zone (KEK) Arun, Aceh, demonstrating promising results with an Internal Rate of Return (IRR) of 11.73%, a Net Present Value (NPV) of USD 166.63 and levelized cost of methanol (LCOM) of 611.61 $/ton MeOH. Compared to other low emission chemical plant, this plant offers promising economic feasibility.

Keywords: blue methanol, natural gas, levelized cost of methanol, carbon capture, MDEA-PZ

Introduction

Methanol is a versatile compound used in various applications, including as a chemical precursor, solvent, plastic, and clean-burning fuel. Recently, methanol has garnered significant attention as a sustainable energy carrier and a potential alternative to conventional fossil fuels. As of 2023, the global market size of methanol has reached USD

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31.26 billion, with a predicted Compound Annual Growth Rate (CAGR) of 4.5% by 2032 (Fortune Business Insights, 2024). Indonesia is projected to reach a market size of 1,900 thousand tons by 2034 with a CAGR of 3.2% (Chemanalyst, 2024).

The production of methanol from natural gas, particularly in Indonesia, presents promising opportunities for the downstream energy sector. Indonesia boasts abundant natural gas reserves, amounting to 46.7 trillion cubic feet (tcf), making it the third largest in the Asia-Pacific region (US Energy Information Adminsitration (EIA), 2021). The nation's commitment to reducing greenhouse gas emissions by 29% by 2030 aligns with the development of cleaner energy pathways, such as blue methanol production (Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia, 2022). This process involves converting natural gas into methanol while capturing the CO2 emissions generated during the process using carbon capture and storage (CCS) systems, which are then either stored or utilized in other applications, thus contributing to a low-carbon economy. This type of methanol is referred to as blue methanol (International Renewable Energy Agency (IRENA), 2021).

Carbon Capture and Storage (CCS) is a critical technology in reducing greenhouse gas emissions from industrial processes. In the context of blue methanol production, CCS plays a pivotal role by capturing CO2 emissions generated during natural gas reforming. The captured CO2 is then either stored underground or utilized in various industrial applications, such as enhanced oil recovery (Al-Shargabi et al., 2022). This integration of CCS with methanol production not only reduces the carbon footprint but also aligns with global sustainability goals, making blue methanol a viable alternative to conventional methanol production (Ugwu et al., 2022).

Economic sustainability in blue methanol production is a crucial factor that determines its adoption and success. Research indicates that the carbon footprint of methanol depends on its feedstock and production pathway, taking into account all emissions directly associated with the supply chain and the energy and materials used within it (Hamelinck, 2022). With the global shift towards sustainability, the techno-economic analysis of such processes becomes increasingly important. This analysis provides insights into the feasibility, cost implications, and environmental benefits of producing methanol in an economically and environmentally friendly manner. This article aims to present a comprehensive overview of the process design for blue methanol production in Indonesia, examining the technical aspects, CCS integration, and economic implications of such endeavors. Through a comparative analysis, we seek to contribute to the body of knowledge on sustainable energy production and offer a roadmap for Indonesia's transition towards a greener future.

Research Method

This study was conducted by designing, synthesizing, and simulating the necessary processes to determine the process parameters and economic parameters for technical and economic analysis (Dimian et al., 2014; Moran, 2019). The processes synthesized in this study underwent a selection process where various process pathways, reaction routes, separation methods, and carbon capture technologies were evaluated and assessed (Cebrucean et al., 2014; Grande et al., 2017; Monjur & Hasan, 2022; Parderio et al., 2022; Salahudeen et al., 2022). After selection, the chosen methods were integrated into the main flow diagram and process flow diagram presented in Figures 1 and 2.

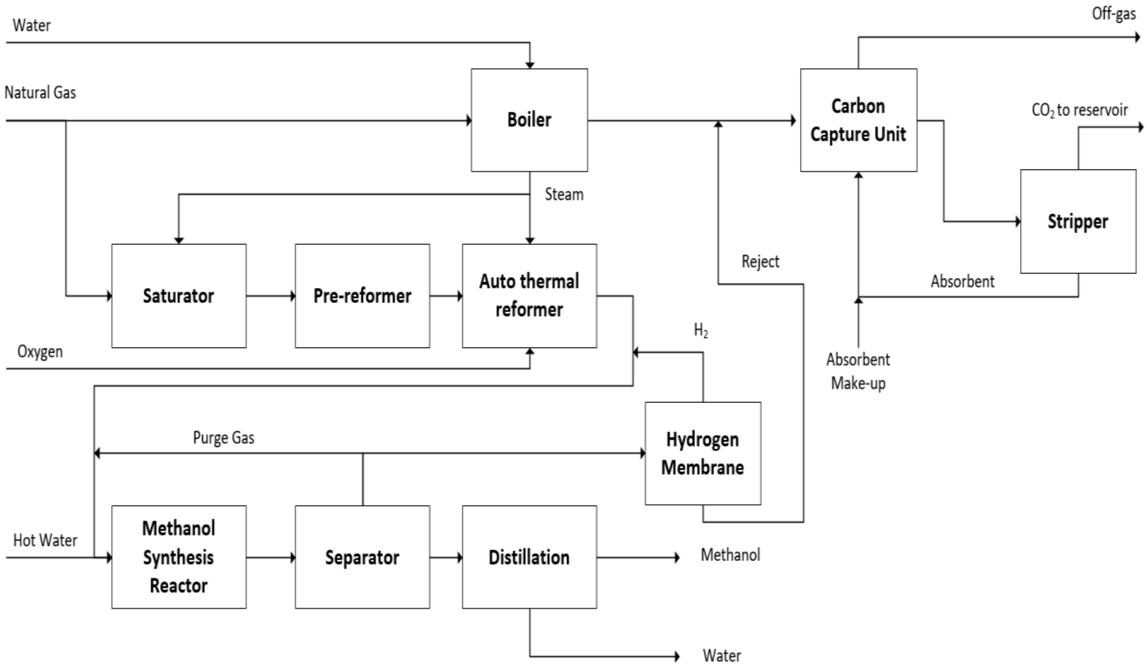

Figure 1 Block flow diagram of blue methanol production from natural gas

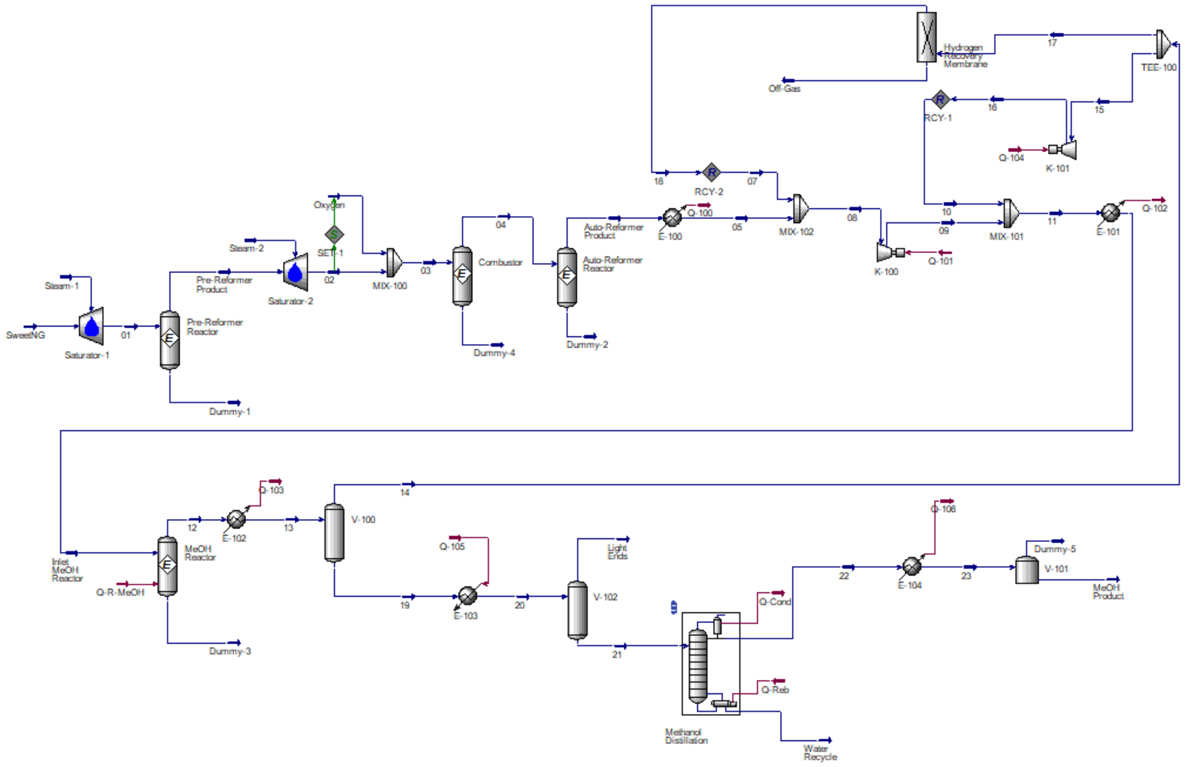

Figure 2 Main process flow diagram of blue methanol production from natural gas

There are five main processes in this methanol production: pre-treatment, syngas formation reaction using an autothermal reformer, methanol formation reaction using a boiling water reactor, methanol separation from exhaust gases, and finally methanol purification. Carbon dioxide (CO_2) contained in the exhaust gases from the main process and boiler utility process is captured using an absorber, resulting in off-gas with CO_2 content of less than 1%.

Natural gas is first pre-treated by mixing it with steam. The mixture is then fed into an adiabatic pre-reformer reactor with a nickel catalyst. In the pre-reformer reactor, hydrocarbons with two or more carbon atoms (C2 and higher) are converted into methane, hydrogen, and carbon oxides through the following series of chemical reactions:

$$C_nH_m + nH_2O \rightarrow nCO + (n + m/2)\ H_2 \tag{1}$$

$$3H_2 + CO \leftrightarrow CH_4 + H_2O \tag{2}$$

$$CO + 2H_2O \leftrightarrow H_2 + CO_2 \tag{3}$$

The product from the pre-reformer is mixed with steam and oxygen with 95% purity and reacted in an autothermal reactor to produce syngas, based on the following chemical reactions:

Combustion:

$$CH_4 + 1½CO \leftrightarrow CO + 2H_2O \quad (4)$$

Catalytic Reactions:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (5)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (6)$$

Syngas is compressed to 50 bar and fed into a boiling water reactor, which produces methanol using $Cu/Zn/Al_2O_3$ catalysts according to the equations:

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \quad (7)$$

$$CO + 2H_2 \leftrightarrow CH_3OH \quad (8)$$

$$CO_2 + H_2 \leftrightarrow CO + H_2O \quad (9)$$

The thermodynamics, reaction mechanisms, kinetics, and catalyst properties of these reactions are discussed in Ertl et al (Ertl et al., 2008). The product from the reactor in the form of crude methanol must go through a purification process before it can be used as the final methanol product. The crude methanol is first cooled to separate it from the remaining reactant gases. After that, the mixture undergoes a flash process to remove the gases, resulting in a purer methanol and water mixture. This mixture is then further separated through distillation to isolate methanol from water. The reactant gases separated from the crude methanol are mostly recycled back into the reactor for reuse. Meanwhile, a portion of these gases is processed to recover hydrogen gas through membrane or adsorption techniques, which are useful for increasing the H_2 ratio in the reactor. Increasing this ratio is known to enhance methanol yield (Kemppainen et al., 2012; Tristantini et al., 2015). The remaining off-gas, which cannot be recycled, then has its carbon content captured using a carbon capture unit before being released into the environment, to reduce carbon emission impacts.

The carbon capture unit consists of a CO2 capture process using activated methyl diethanolamine (MDEA) and absorbent regeneration. Research shows that adding piperazine (PZ) to the MDEA solution significantly enhances CO2 absorption efficiency. This advantage is due to the very fast reactivity of piperazine with CO2, which accelerates the absorption process in the absorber column. Additionally, this system maintains low regeneration heat in the stripper section, which is crucial for the overall energy efficiency of the gas separation process by up to 7.66% (Saleh et al., 2021; Zhao et al., 2017). The CO2 capture unit is shown in Figure 3.

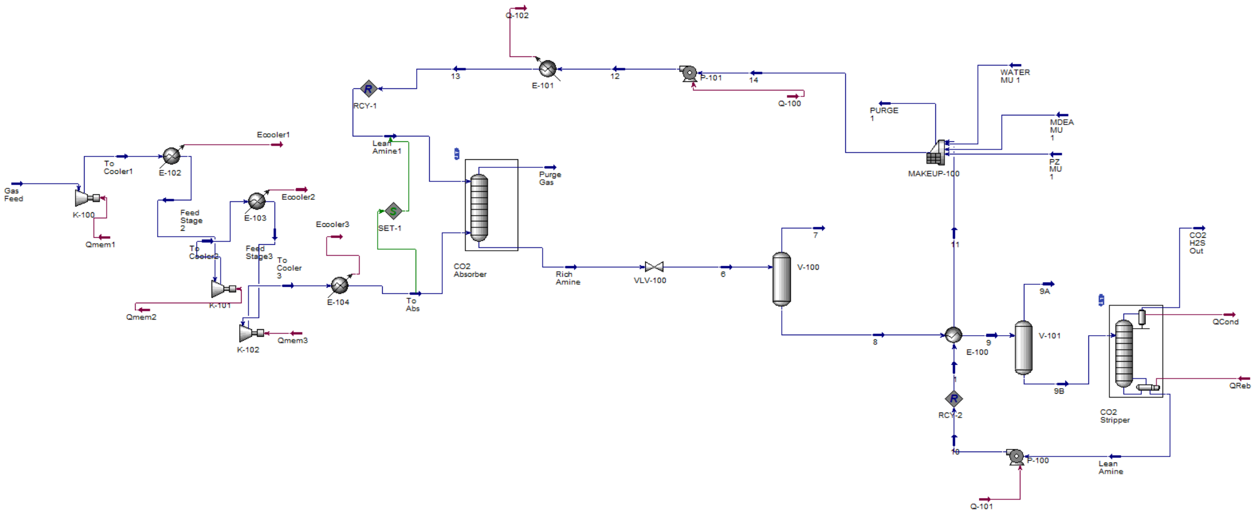

Figure 3 Process flow diagram of CO2 capture using activated MDEA+PZ

Several software tools were used to perform calculations related to this plant. Mass and energy balance calculations were carried out using Aspen HYSYS V10 software, a widely recognized software in the chemical engineering field. Aspen HYSYS was employed to model the entire methanol production process, ensuring accurate mass and energy balance calculations. To validate the accuracy of the simulation results, the model was calibrated against existing peer-reviewed studies. This step was crucial in ensuring that the process design reflects real-world operational conditions, thereby enhancing the reliability of the techno-economic analysis.

Economic calculations were performed using spreadsheet software. Data related to the free on-board cost of process equipment, utilities, operational costs, total bare module factor, and equipment cost were based on assumptions from Seider et al (Seider et al., 2009). The Levelized Cost of Methanol (LCOM) represents the cost required to produce methanol, which may involve the effect of carbon tax on methanol pricing (Tjahjono et al., 2023), calculated by the formula:

$$LCOMTotalOperatingCost \tag{10}$$

This methanol plant will be constructed on a pilot scale with a capacity of 100,000 tons per year, located in the Arun Special Economic Zone (SEZ) in the administrative area of North Aceh Regency, Lhokseumawe City, Aceh Province. This area is designed as a center for industrial and economic development, providing infrastructure and facilities that support the growth of strategic economic sectors in the Aceh region.

Result and Discussion

The design process for the equipment was meticulously conducted to ensure suitability and performance in production. Aspen HYSYS was used to calculate and optimize the equipment specifications, as has been done in several other studies (Ali et al., 2021; Noaman, 2022; Sotelo et al., 2021). This approach allows for the efficient and compatible design of key stages in the production flow, including the pre-reformer reactor, autothermal reactor, methanol synthesis reactor, distillation column, and absorption column, adhering to strict industrial standards. A summary of the main process equipment is presented in Table 1.

Table 1 Specifications of key equipment for blue methanol production

Equipment	Flow Rate (kg/h)	Temperature (°C)	Diameter (mm)	Height (mm)
Pre-Reformer Reactor	857.6	400-500	1,366	2,048
Auto-Thermal Reformer	1,968.15	850-950	1,503	4,510
Methanol Synthesis Reactor	3,958.95	200-250	1,503	2,255
Methanol Distillation Column	1,693.45	Feed: 65-75	54.30	1,036
Absorption Column	Absorbent: 1,242.30 Feed: 241.73	40-60	114.64	6,096
Stripper Column	1,275.62	Feed: 100-110	294.30	609.60

The electrical and water requirements for the plant utilities have been calculated. The electricity requirement was determined by summing the power consumption of each piece of equipment based on simulations performed in Aspen HYSYS. This result was then multiplied by a correction factor of 1.25 to account for potential power losses along the lines and the need for backup power. The estimated electrical power required for the plant is 265.42 kW per hour for direct power and 34.5 kW per day for office electricity and supporting facilities. The daily electricity consumption cost is calculated to be USD 606.29.

Water usage in the plant is categorized into process water and domestic water. Process water requirements were calculated based on the amount of water needed at each production stage, including steam, estimated to be 563,360 kg per hour. Domestic water usage was calculated for drinking, toilets, laboratory, mosque, canteen, and gardens, with a total domestic water usage of 4,000 kg per day (Dieter et al., 2018).

The methanol production plant utilizes torrefied empty palm bunches as a primary fuel due to their lower emissions. Torrefaction enhances the combustion efficiency of palm bunches, resulting in fewer greenhouse gas emissions compared to traditional fuels (Nabila et al., 2023). By using these agricultural by-products, the plant reduces its carbon footprint and supports sustainable energy practices, aligning with its commitment to environmentally friendly operations. The empty fruit bunches needed is 1.54 tonne/day.

The economic analysis of the plant was conducted by calculating the capital expenditures (CAPEX) and operational expenditures (OPEX). Capital expenditures include the total cost of equipment, site development, building construction, off-site facilities, contingency costs, contractor fees, working capital, supporting facilities, bulk material costs, and other additional costs, calculated using factors from Garrett et al. with adjustments (Garrett, 1989). The details of CAPEX are shown in Table 2.

Table 2 Total capital expenditure

Expense Category	Amount (USD)
Process Equipment	20,516,622.67
Site Development	77,142,501.25
Building Construction	57,856,875.94
Offsite Facilities	7,714,250.12
Working Capital	11,571,375.19
Plant Start-up & Contingency	4,628,550.07
Total	158,913,552.57

Operational expenditures include the costs of raw materials, utilities, labor, maintenance, insurance, distribution, marketing, and depreciation. A summary of OPEX can be seen in Table 3.

Table 3 Total operational expenditure

Expense Category	Amount (USD/year)
Raw Material Costs	25,754,860.22
Utility Costs	23,022.91
Labor and Labor-related Costs	28,857.89
Capital Related Cost (maintenance, depreciation, plant overhead)	19,154,483.06
Distribution and Marketing Costs	16,200,000.00
Total	61,161,224.07

Profitability analysis was performed by calculating revenue and cash flow. Revenue was calculated from product sales after deducting taxes and operational costs. Product sales were predicted using an integrated supply chain model. Cash flow was calculated by subtracting total expenditures from total revenue, and cumulative cash flow is displayed in Figure 4.

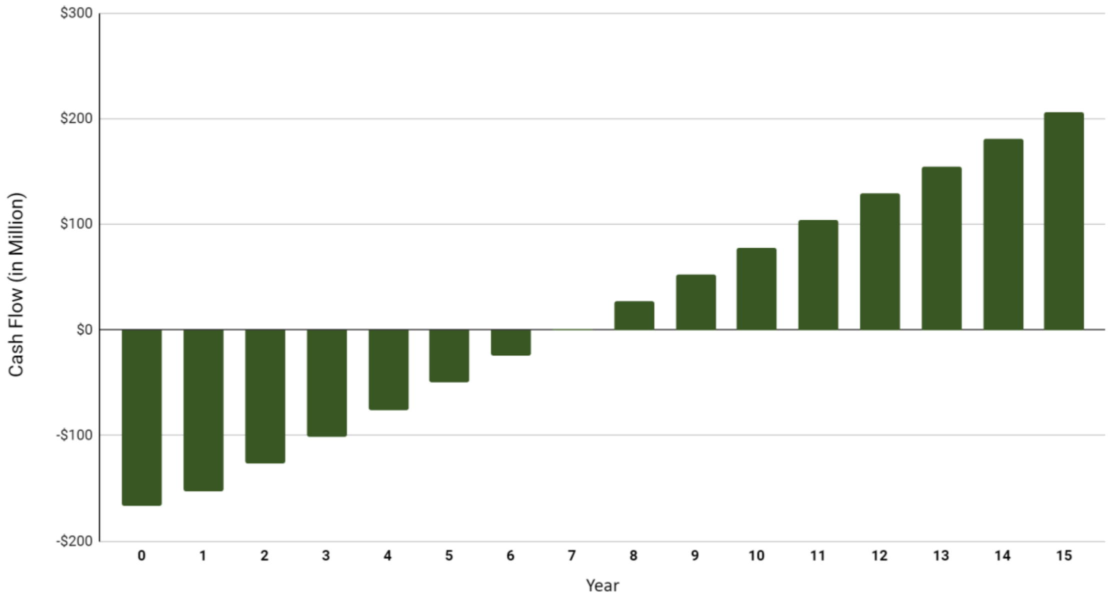

Figure 4 Cumulative cash flow

Based on the calculated cash flow, the plant's profitability was analyzed using several key financial indicators such as the Internal Rate of Return (IRR), Net Present Value (NPV), Payback Period, Rate of Return (ROR), and Levelized Cost of Methanol (LCOM). The results of this profitability analysis are presented in Table 4.

Table 4 Profitability analysis

Component	Value
IRR	11.73%
NPV (in USD)	166,627,802.69
Payback Period	6.96
ROR	10,24%
LCOM (in USD)	611.61

ROR indicates the acceptable investment ratio to start a project, considering the associated risks and opportunity costs (Park, 2007). Therefore, the obtained IRR must be greater than the ROR and bank interest rate for the project to be deemed profitable. According to the calculations, the obtained ROR and IRR are 11.73% and 10.24%, respectively, which are higher than the assumed bank interest rate of 10%. The calculated Payback Period indicates the number of years required to recover all the invested funds or reach the break-even point. The Payback Period for this plant is 6.96 years, which is relatively long for a methanol plant (Deka et al., 2022). NPV is used to determine the value of an investment over a specific period. The NPV obtained for this plant is USD 166.63 million, only 4.85% higher than the initial capital investment. Meanwhile, the LCOM of this methanol plant is 611.61 $/ton of methanol without carbon tax. The economics of this plant is then compared with other studies. The comparison of various methanol production processes are shown in Table 5 below.

Table 5 Comparison of various methanol production processes

Comparison Criteria	Study/Source	NPV (USD Million)	IRR (%)	LCOM	Carbon Tax
Conventional Methanol from Coal	Suganal et al., 2021	289.7	13.35	-	No carbon tax
Methanol from Natural Gas (without CCS)	Arnaiz del Pozo et al., 2022	-	-	268.5 €/ton	0.35 €/ton CO2
Blue Methanol using Green Hydrogen	Martanto et al., 2023	-	-	1,960.87 USD/ton	No carbon tax
Methanol from Bio-CNG (Compressed Natural Gas)	Sheets & Shah, 2018	43 (purified biogas)	7%	2,240 USD/ton	No carbon tax
Methanol from Shale Gas	Yang & You, 2018	Negative	-	-	No carbon tax

Methanol production from coal in Indonesia, as reported by Suganal et al. (2021), demonstrates strong economic viability with an NPV of 289.7 million USD and an IRR of 13.35%. This is a significant benchmark, highlighting the attractiveness of coal-based methanol production in the absence of environmental regulations such as a carbon tax. In contrast, methanol production from natural gas without carbon capture, as studied by Arnaiz del Pozo et al. (2022), shows a much lower LCOM of 268.5 €/ton of methanol. This suggests that, despite the lower costs, the absence of carbon capture could limit the environmental appeal of this method, particularly as global regulations on carbon emissions become stricter.

The production of blue methanol using green hydrogen, analyzed by Martanto et al. (2023), shows a significantly higher LCOM of 1,960.87 USD/ton. This high cost reflects the premium associated with green hydrogen, which, while environmentally favourable, presents economic challenges in terms of competitiveness, especially without the implementation of a carbon tax. Sheets and Shah (2018) provide insight into methanol production from bio-CNG, which, despite having an NPV of 43 million USD for purified biogas, suggests that bio-CNG may be less economically viable compared to conventional methods. However, the use of bio-CNG aligns with renewable energy goals, potentially offering long-term benefits in terms of sustainability. Lastly, methanol production from shale gas, as studied by Yang and You (2018), resulted in a negative NPV, indicating an economically unviable option. This result underscores the financial risks associated with shale gas methanol production, further emphasizing the need for more cost-effective and sustainable alternatives. Overall, the blue methanol plant in this study, while less attractive to investors compared to conventional coal-based methanol production, holds promise when compared to other environmentally targeted methods. Its economic performance, particularly in the context of Indonesia's goals to decarbonize its downstream industry, suggests that with appropriate policy support and technological advancements, it could become a key player in the future of sustainable methanol production.

Conclusions

The production of blue methanol in Indonesia is considered feasible to support the decarbonization of the downstream industry. By leveraging abundant natural gas reserves and carbon capture and storage (CCS) technology, the blue methanol production process not only reduces carbon emissions but also offers competitive production costs. This study shows that despite having a relatively long payback period, blue methanol production in Indonesia demonstrates strong economic potential with an IRR of 11.73% and an NPV of USD 166.63 million. The LCOM for this plant is also relatively low for the chemical industry.

While the study demonstrates the technical and economic feasibility of blue methanol production in Indonesia, several limitations must be acknowledged. The economic analysis is sensitive to fluctuations in natural gas prices and policy changes, which could impact the project's viability. Additionally, the long payback period may pose challenges in securing investment. Future research should explore alternative feedstocks, such as biomass, and investigate the potential for integrating renewable energy sources into the methanol production process. These avenues could further enhance the sustainability and economic competitiveness of blue methanol. With the right development strategies and adequate policy support, blue methanol plants can significantly contribute to Indonesia's energy sector decarbonization and support the transition towards a low-carbon economy.

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