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Techno-Economic Risk Analysis of CO2 and Hydrogen Utilization for Dimethyl Ether Production

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Abstract

The increasing global emphasis on carbon footprint reduction and advancements in Carbon Capture, Utilization, and Storage (CCUS) technologies have spurred interest in converting CO_2 into value-added products such as Dimethyl Ether (DME), an environmentally friendly alternative fuel. This study assesses the techno-economic viability of DME production from CO_2 and methane (CH_4) in Indonesia, where dependence on imported Liquefied Petroleum Gas (LPG) presents a significant challenge. Utilizing Aspen Plus for process simulation and Monte Carlo methods for quantitative risk analysis, the research evaluates key techno-economic indicators: Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP), and Profitability Index (PI). The simulation results indicate a daily DME production capacity of 868.04 tons, with an NPV of USD 1.78 billion, IRR of 58.44%, PBP of 2.041 years, and PI of 3.675—demonstrating robust project viability within the techno-economic risk analysis framework. The Monte Carlo simulations reveal minimal financial risk, as all economic parameters remain positive across 1,000 iterations, indicating strong project resilience against input uncertainties. Sensitivity analysis identifies the DME selling price as the most critical variable affecting project economics. These findings support Indonesia’s strategy to implement DME as a substitute for LPG, providing a sustainable approach to reducing energy import dependency while leveraging CCUS technologies. The research offers actionable insights for policymakers and investors, highlighting both economic and environmental advantages associated with CO_2 utilization in alternative fuel production.

Keywords: *CCU,CO2, CH4, DME,techno-economic analysis, risk analysis*

INTRODUCTION

Carbon Capture, Utilization, and Storage (CCUS) is a topic being rapidly developed globally, as it is considered a potential solution to global climate change challenges. CCUS works by capturing and injecting CO_2 into rock formations or utilizing CO_2 as a raw material in various applications (Global CCS Institute, 2018). Carbon Capture and Utilization (CCU) can create new economic opportunities by converting CO_2 into value-added products such as alternative fuels, chemicals, building materials, and others.

In 2022, Indonesia imported 47,741 tons of oil and gas to meet domestic energy needs. Liquefied Petroleum Gas (LPG), which is commonly used in daily household activities, requires significant imports. Indonesia's LPG consumption in 2030 is predicted to reach 9.7 million metric tons per year, with domestic supply from natural gas processing facilities at 1.2 million metric tons per year and from local refinery production at 1.8 million metric tons per year (Minister of Energy and Mineral Resources, 2021). From this data, it is evident that more than 50% of

Indonesia's LPG supply comes from imports. Dimethyl Ether (DME) is one solution to this problem. As an alternative supplementary fuel, DME is mixed with LPG to improve combustion and reduce harmful emissions. Currently, studies are underway regarding increasing the ratio of DME in the mixture to reduce dependence on LPG. DME can be produced using methane and CO_2 as raw materials. Therefore, the utilization of CO_2 as a raw material for DME production has urgency to be further reviewed regarding the feasibility of its investment realization. Additionally, high-purity DME is also used in industries as an aerosol propellant and as a solvent.

Dimethyl Ether (DME) is a chemical solvent and environmentally friendly alternative fuel, replacing diesel and LPG due to its good combustion and low emissions. DME is also used as an aerosol propellant and synthesis chemical. The Indonesian government plans to replace LPG with DME by 2030, with LPG demand predicted to increase from 7.5 million tons to 10 million tons, where 45% will be replaced by DME (Ministry of Energy and Mineral Resources, 2021).

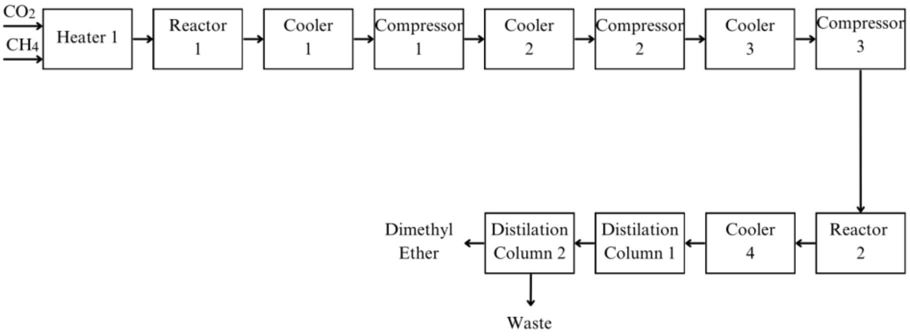


Figure 1. Dimethyl ether production block flow diagram

The production of Dimethyl Ether (DME) from CO_2 and methane involves an indirect method through three key process units, as illustrated in Figure 1. The Dry Reforming Methane (DRM) unit, marked in red, converts CH_4 and CO_2 into syngas at 700°C and 1.013 bar, following the stoichiometric reaction with a CO_2 conversion rate of 78%, based on data from Merkouri et al. (2022). The syngas then proceeds to the Direct DME Production unit (black line), where it undergoes methanol synthesis via reactions 2.2–2.4, followed by methanol dehydration to produce DME (reaction 2.5). Kinetic factors for these reactions, sourced from A.A. Kiss et al. (2016), guide the simulation, with the reactor operating at 250°C and 50 bar in a multi-tubular plug-flow design. Finally, the DME Purification unit (blue line) employs multi-stage distillation to isolate high-purity DME from impurities.

Economic evaluation of the DME production process relies on key parameters such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP), and Profitability Index (PI). NPV assesses project feasibility by discounting net cash flows to their present value, with positive values indicating viability (Equation 2.6). IRR, calculated using Equation 2.7, measures the project's return rate, requiring it to exceed the Minimum Acceptable Rate of Return (MARR). PBP estimates the time needed to recoup the initial investment (Equation 2.8), while

PI evaluates profit potential, with values greater than 1 signifying a profitable venture (Equation 2.9). These metrics collectively ensure the project's financial soundness and attractiveness to investors.

To account for uncertainties in the process, Monte Carlo simulation is employed as a statistical technique. This method generates random input values within defined standard deviations to model a range of possible outcomes, identifying the most probable, highest, and lowest results. The simulation follows four steps: calculating average input values, determining standard deviations, generating random values, and running simulations with these inputs. This approach provides a robust assessment of risk and variability, enabling more informed decision-making in the face of operational and economic uncertainties.

The integration of these technical and economic analyses ensures a comprehensive evaluation of DME production from CO_2 and methane. By combining process simulations with financial metrics and risk assessments, the study offers a holistic view of the project's feasibility, profitability, and potential challenges. This dual focus on engineering and economics is critical for advancing sustainable fuel production technologies while ensuring their commercial viability in a competitive energy market.

RESEARCH METHOD

In this research method, the stages required to achieve the final simulation results are explained. The research begins with the collection of literature, simulation data, and economic calculations as the basis for conducting the research. The research will be conducted following the flow in the diagram in Figure 2.

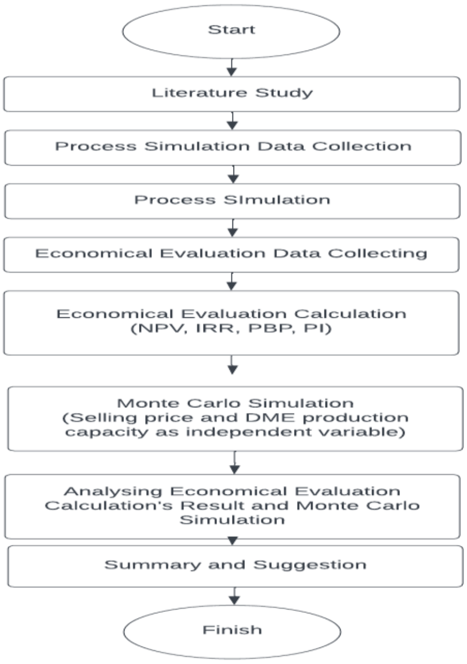


Figure 2 Research process flow diagram

The independent, control, and dependent variables in this research are, respectively: the selling price of DME, raw material prices, and catalyst prices; process operating conditions, raw material flowrate, final product composition, CAPEX, and OPEX; NPV, IRR, PI, and PBP.

RESULT AND DISCUSSION

Process Simulation

In this research, the NRTL-RK fluid package is used, referring to A.A. Kiss et al, 2016. The NRTL fluid package was chosen due to its accuracy in predicting phase equilibrium for non-ideal system mixtures. Meanwhile, Redlich Kwong is a thermodynamic model capable of handling high-pressure operating conditions commonly found in DME production processes. Table 1 contains the initial feed conditions.

Table 1. Feed condition

Parameter	CO_2 Feed	CH_4 Feed
Temperature (°C)	25	25
Pressure (Bar)	1	1
Flowrate (kg/jam)	91,000	31,000
	Mass fraction	
CO_2	1	0
CH_4	0	1

This research begins with heating the feed to 700°C using a heater in the Aspen Plus simulation. The stream is directed to a stoichiometric type DRM reactor at a temperature of 700°C, pressure of 1.013 bar, and CO_2 fraction conversion of 0.78 (Merkouri et al., 2022). Next, the stream is compressed to 50-100 bar and 250-300°C for methanol synthesis (A.A. Kiss et al., 2016), passing through three compressors and coolers. Then, the stream is reacted in the DME reactor using PFR (Table 4). After production, the stream is passed through four distillation columns to achieve a DME purity of 99.97%. The Aspen Plus simulation is shown in Figure 3.

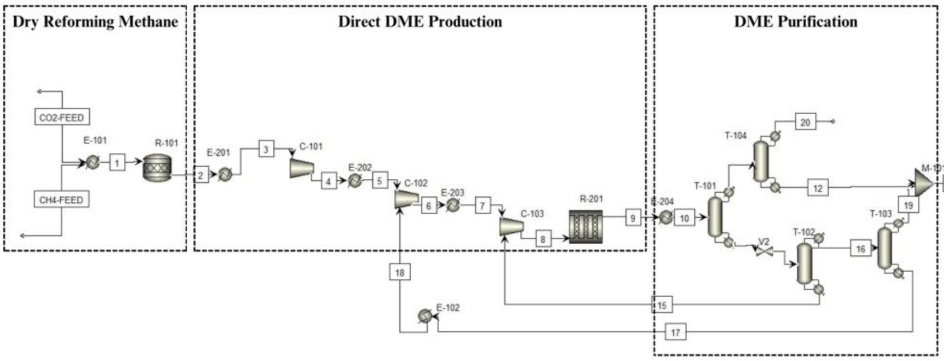


Figure 3 DME production simulation flowsheet on Aspen Plus

From the simulation in Figure 3, DME is produced with specifications shown in Table 2.

Table 2. DME Specification

Parameter	Value
Temperature (°C)	-25.195
Pressure (Bar)	1
Flowrate (kg/jam)	32811.3
Mass Fraction	
CH_4	1.955e-9
CO_2	0.00034
H_2	9.165e-58
CO	5.171e-18
H_2O	2.785e-10
DME	0.999

Economic Calculation Assumptions

For economic calculations, several assumptions are needed as calculation references. In this research, the following assumptions are used:

a) The plant operates for 350 days each year for 20 years starting in 2026.
b) The plant is built within a refinery area that supplies CO_2 captured from the refinery's carbon capture unit, the cost of which is not calculated because it is outside the scope of this research.
c) Income tax in Indonesia is 25% (Government Regulation No. 46 of 2013).
d) The price of high purity DME (99.9%) ranges from USD 1300-USD 2000 per ton.
e) The electricity cost used is green electricity from PLN biogas.
f) The CEPCI value used for 2024 is 676.77.
g) The USD to IDR conversion rate is set at the price as of May 22, 2024, which is Rp. 16,085 per 1 USD.
h) The plant operates with 3 operator shifts per day.

Capital Cost Calculation

Economic calculation begins with calculating the bare module cost (C_{BM}) from free on-board using equation 4.1.

$$C_{BM} = C_P F_{BM}^{O} = C_P(B_1 + B_2 F_M F_P) \qquad 4.1$$

Where:

C_P = Purchase cost
F_{BM}^{O} = Bare module factor
F_M = Material factor
F_P = Pressure factor

The F_M value depends on the type of material used. In this research, all equipment uses stainless steel with properties shown in Table 3

Table 3. Properties of stainless-steel material

Parameter	Value
Maximum allowable stress (S)	16000 psi
Weld efficiency (E)	0,9
Minimum allowable vessel thickness (t_{min})	0,0063 m
Corrosion allowance (CA)	3,15 mm

After the prices of all equipment are known, they are summed as C_{TBM} (total bare module) (Van Amsterdam, 2018). From C_{TBM}, C_{TDC} (total depreciable capital) can be calculated with equation 4.2.

$$C_{TDC} = F_{indirect} C_{TBM}(1 + F_B + F_O + F_Y) \qquad 4.2$$

Where:

$F_{indirect}$ = 1.18 (contractor and contingency costs of 3% and 15% of CTDC)
F_B = Building factor (0.03)
F_O = Off-site facilities factor (0.20)
F_Y = Site development factor (0.05)

Thus, the simplified equation 4.3 is obtained.

$$C_{TDC} = 1.51 C_{TBM} \qquad 4.3$$

Next, C_{TDC} is used to estimate C_{TPI} (total permanent investment) through equation 4.4 (Seider et al., 2016).

$$C_{TPI} = C_{TDC} + C_{land} + C_{royalties} + C_{startup} \qquad 4.4$$

Where:

C_{land} = Land cost (2% C_{TDC})
$C_{royalties}$ = Royalty cost (2% C_{TDC})
$C_{royalties}$ = Plant startup cost (10% C_{TDC})

Based on (Seider et al., 2016), C_{WC} (working capital cost) is 15% C_{TPI}, so C_{TCI} can be seen in equation 4.5.

$$C_{TCI} = C_{TPI}(1 + 0.15) = 1.15 C_{TPI} \qquad 4.5$$

Based on the equations above, the calculation from bare module cost to total capital investment is shown in Tables 4 and 5.

Table 4 Bare module cost calculation

Code	Bare Module Factor	Total Price (USD)	Total Price (IDR)
		Reactor	
R-101	4.16	8,671,135	139,475,219,954
R-201	4.16	100,169,855	1,611,232,119,029
		Compressor	
C-101	2.15	18,774,454	301,987,097,891
C-102	2.15	33,907,958	545,409,508,975
C-103	2.15	41,260,762	663,679,370,340
		Heat Exchanger	
E-101	3.17	109,410	1,759,866,658
E-201	3.17	237,679	3,823,076,506
E-202	3.17	138,145	2,222,072,436
E-203	3.17	289,919	4,663,355,321
E-204	3.17	229,577	3,692,749,782
E-102	3.17	44,380	713,866,411

Code	Bare Module Factor	Total Price (USD)	Total Price (IDR)
	Distillation Column		
T-101	4.16	1,880,316	30,244,895,990
T-102	4.16	599,095	9,636,458,017
T-103	4.16	489,130	7,867,666,261
T-104	4.16	592,471	9,529,897,761
	Storage Vessel		
V-101	3.49	1,013,897	16,308,548,289
TOTAL		208,408,192	3,352,245,769,631

Table 5. Capital cost calculation

Cost Type	Price (USD)
Total Depreciable Cost (CTDC)	314,696,370
Total Permanent Investment (CTPI)	358,753,861
Total Capital Investment (CTCI)	412,566,941

Calculation of Annual Cost

Annual cost (OPEX) calculation is divided into several types of costs, which is direct costs, fixed costs, and general expenses. According to Turton et al. (2018), Table 6 shows the equations for estimating direct costs.

Table 6. Direct Cost Equations

Cost	Description	Equation
Raw materials	Costs of LNG (CH_4), DRM catalyst, and DME catalyst	C_{RM} = Total cost of raw materials
Utilities	Costs of cooling water, low pressure steam, fired heater, and electricity	C_{UT} = Total cost of utilities
Number of Operators	Total number of operators	$N_{OL} = \left(6.29 + 31.7P^2 + 0.23N_{np}\right)^{0,5}$
Operators	Total operator costs	$C_{OL} = N_{OL} \cdot$ Operator salary
Supervision and administration	Costs of engineering, administration, and support workers	0.18 C_{OL}
Maintenance	Costs of maintenance and repair of plant equipment	0.06 C_{TPI}
Laboratory	Costs of LNG (CH_4) and catalysts	0.15 C_{OL}
Operating support	Production support costs	0.009 C_{TPI}

(Source : Turton et al. (2018))

Table 7. C_{RM} Calculation

Raw Material	**Amount**	**Unit (/Year)**	**Price per Unit (USD)**	**Cost (USD)**
CO_2	842,607.500	ton	-	-
CH_4	13,706,400	MMBTU	9.79	134,185,656.00
DRM Catalyst	137,160.2	Kg	70	9,601,212.33
DME Catalyst	235,149.297	Kg	50	11,757,464.85
Total Cost (C_{RM})				155,544,333.185

Table 7 shows the calculation for raw material costs. CO_2 cost is not calculated as per the assumption, CH_4 cost is taken from the LNG price. The catalyst used for DRM is 10 wt.% Ni-substituted on the B-site of the $La_2Zr_2O_7$ pyrochlore (LNZ_{10}) and the catalyst for DME is CuO–ZnO–Al_2O_3 (CZA), with both catalysts being replaced every 6 months.

Table 8. C_{UT} Calculation for Years 1-10

Utility	**Amount**	**Unit (/Year)**	**Price per Unit (USD)**	**Cost (USD)**
Cooling Water	142,846,935	Ton	0.03	3,874,723.11
LP Steam	2,762.057	Ton	7.30	20,163.01
Fired Heater	2,108,550.500	Ton	-	-
Electricity	16,361,422	kW	0.82	13,390,187.76
Total Cost (C_{UT}) Years 1-10				17,285,073.889

Table 9. CUT Calculation for Years 11-20

Utility	**Amount**	**Unit (/Year)**	**Price per Unit (USD)**	**Cost (USD)**
Cooling Water	142,846,935	Ton	0.03	3,874,723.11
LP Steam	2,762.057	Ton	7.30	20,163.01
Fired Heater	2,108,550.500	Ton	-	-
Electricity	16,361,422	kW	0.49	8,026,913.63
Total Cost (CUT) Years 11-20				11,921,799.758

In Tables 8 and 9, the fired heater cost is not calculated because it comes from the heat integration of the refinery furnace. Electricity is assumed to be from PLN biogas power at a price of USD 0.82/kWh for years 1-10, decreasing to USD 0.49/kWh for years 11-20 (Riyandanu, 2022). For N_{OL}, P is considered 0 because there is no solid handling, and N_{np} is 3 because there are 3 process units, so 9 operators per shift are needed. The calculation of direct costs can be seen in Tables 10 and 11.

Table 10 Direct Cost Calculation for Years 1-10

Cost Type	Cost (USD)
Raw materials	155,544,333.19
Utilities	17,285,073.89
Operators	1,980
Supervision and administration	356.40
Maintenance	21,525,231.71
Laboratory	297
Operating support	3,228,784.76
Total	197,586,056.94

Table 11 Direct Cost Calculation for Years 11-20

Cost Type	Cost (USD)
Raw materials	155,544,333.19
Utilities	11,921,799.76
Operators	1,980
Supervision and administration	356.40
Maintenance	21,525,231.71
Laboratory	297
Operating support	3,228,784.76
Total	192,222,782.81

According to Turton et al. (2018), Table 11 shows the equations for estimating fixed costs.

Table 12 Fixed Cost Equations

Cost	Description	Equation
Depreciation	Physical plant costs such as buildings and equipment	C_{DEP}
Local taxes and insurance	Property tax and insurance costs	0.032 C_{TPI}
Plant overhead	Support facility costs such as fire equipment, employee benefits, etc.	0.036 C_{TPI} + 0.708 C_{OL}

C_{DEP} is calculated using C_{TBM} as a reference for book value. The depreciation factor needs to be known with equation 4.6.

$$C_{DEP}\ Factor = 1 - \left(\frac{5000}{C_{TBM}}\right)^{\frac{1}{20}} \qquad 4.6$$

The C_{DEP} value is calculated with equation 4.7.

$$C_{DEP} = C_{DEP}\ Factor \times C_{TBM_{n-1}} \qquad 4.7$$

Thus, the plant depreciation calculation for 20 years is shown in Table 12.

Table 12. Depreciation

Year		Process Equipment		
		Factor	Depreciation (USD)	Book Value (USD)
0	2025	-	-	208,408,192
1	2026	0.413	85,969,820	122,438,372
2	2027	0.413	50,506,675	71,931,697
3	2028	0.413	29,672,322	42,259,375
4	2029	0.413	17,432,284	24,827,091
5	2030	0.413	10,241,347	14,585,744
6	2031	0.413	6,016,720	8,569,024
7	2032	0.413	3,534,782	5,034,242
8	2033	0.413	2,076,660	2,957,583
9	2034	0.413	1,220,023	1,737,559
10	2035	0.413	716,755	1,020,804
11	2036	0.413	421,089	599,715
12	2037	0.413	247,387	352,329
13	2038	0.413	145,338	206,991
14	2039	0.413	85,385	121,606
15	2040	0.413	50,163	71,442
16	2041	0.413	29,470	41,972
17	2042	0.413	17,314	24,658
18	2043	0.413	10,172	14,487
19	2044	0.413	5,976	8,511
20	2045	0.413	3,511	5,000

Other costs for fixed costs are shown in Table 13.

Table 13. Fixed cost calculation

Cost Type	**Cost ($)**
Local taxes and insurance	11,480,123.58
Overhead	12,916,540.87
Total	24,396,664.45

According to Turton et al. (2018), Table 14 contains equations for estimating general expenses.

Table 14 General expense equations

Cost	**Description**	**Equation**
Product distribution and sales	Distribution, sales, marketing costs, etc.	$0.11\ C_{OM}$
Research and development	Product and process research costs	$0.05\ C_{OM}$

Administration	Salary costs, building administration, etc.	$0.009\ C_{TPI} + 0.177\ C_{OL}$
Patents and Royalties	Costs of using patents and royalties	$0.03\ C_{OM}$

(Source : Turton et al. (2018))

The difference in total direct costs in years 1-10 and years 11-20 affects the calculation of general expenses. Thus, general expenses for years 1-10 and years 11-20 are obtained in Tables 15 and 16.

Table 15. General expense calculation for years 1-10

Cost Type	**Cost ($)**
COM	221,982,721.39
Product distribution and sales	24,418,099.35
Research and development	11,099,136.07
Administration	3,229,135.22
Patents and Royalties	6,659,481.64
Total	45,405,852.28

Table 16. General expense calculation for years 11-20

Cost Type	**Cost ($)**
COM	216,619,447.26
Product distribution and sales	23,828,139.20
Research and development	10,830,972.36
Administration	350.46
Patents and Royalties	6,498,583.42
Total	41,158,045.44

The three types of costs are combined and summed to obtain OPEX; depreciation is not included in this sum because it will be detailed separately in the cash flow. The difference in total direct costs in years 1-10 and years 11-20 affects the calculation of annual costs. Thus, annual costs for years 1-10 and years 11-20 are obtained in Tables 17 and 18.

Table 17. Total annual cost calculation for years 1-10

Annual Cost	**Cost ($)**
Total annual cost	197,586,057
Total fixed cost	24,396,664
Total general expenses	45,405,852
Total Years 1-10	267,388,574

Table 18. Total annual cost calculation for years 11-20

Annual Cost	**Cost ($)**
Total annual cost	192,222,783
Total fixed cost	24,396,664

Total general expenses	41,158,045
Total Years 11-20	257,777,493

Cash flow calculation refers to Turton et al., 2018 in Table 19.

Table 19. Cash Flow Equations

Cost	Description	Equation
Expenditure	Total CAPEX, OPEX, and depreciation	$C_{OMd} + d$
Income Tax	Net income multiplied by income tax	$(R - C_{OMd} - d)(t)$
Net profit after tax	Net income minus income tax	$(R - C_{OMd} - d)(1-t)$
Cash flow after tax	Total net profit and depreciation	$(R - C_{OMd} - d)(1-t) + d$

Based on Table 19, cash flow is calculated from construction until the plant ceases operation. The percentage of products sold rises from 70% (2026) to 100% (2029-2042) and falls to 70% (2045), reflecting the beginning of a new plant and declining productivity.

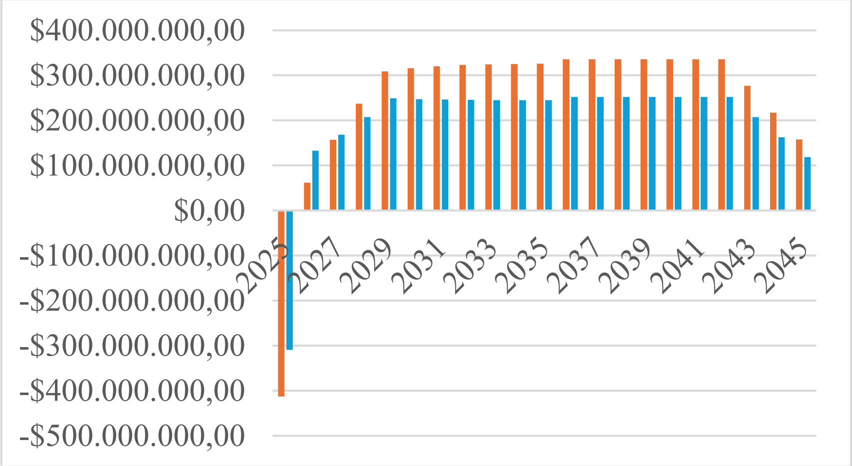


Figure 4. Cash Flow Graph

Figure 4 shows the cash flow graph in this research where orange line is net cash flow and blue line is cash flow after tax, this graph showing production capacity adjustments in the first 3 years of productive plant operation and assumed decline in equipment operational capability causing production capacity reduction in the last 3 years of production.

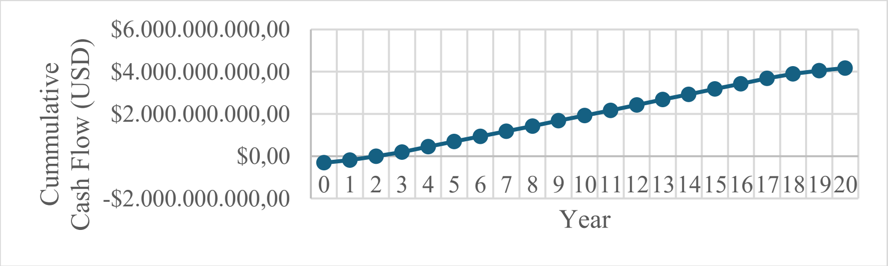
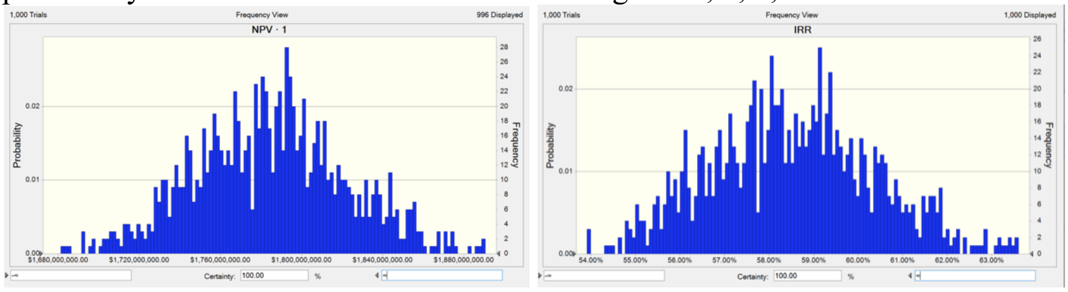


Figure 5 Cumulative Cash Flow Graph

Figure 5 shows the cumulative cash flow where in years 0-2, the plant's cash flow is still negative or has not reached profit conditions. Afterward, in years 3-20, profitable cash flow is observed. From the cash flow, economic parameter values obtained are NPV of $1,783,715,566.19, IRR of 58.44%, PBP of 2.041 years, and PI of 3.675.

Discussion

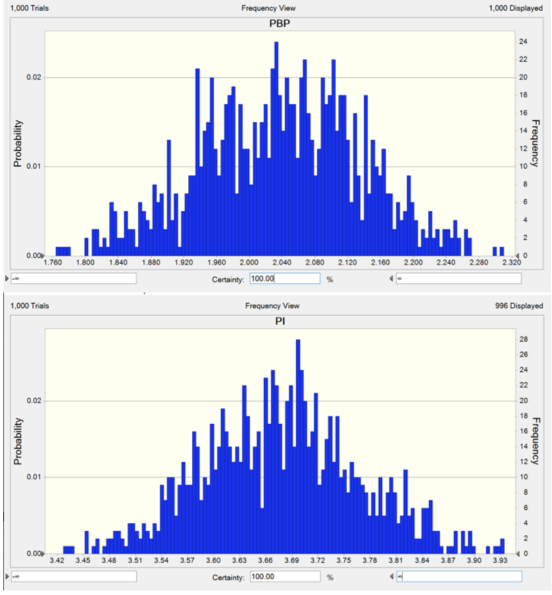
In this chapter, evaluation and analysis of the economic calculation results will be performed, starting with risk evaluation using Monte Carlo simulation. The probability distribution results can be seen in Figures 6, 7, 8, and 9.



(a) (b)

Figure 6 Monte Carlo a) NPV and b) IRR

The Monte Carlo simulation results for NPV can be considered profitable, as seen from the minimum value showing a positive value of $1,661,028,713.55. IRR shows values that are always positive with a minimum value of 53.91%. It is concluded that the plant in this research has minimal risk in terms of NPV and IRR.



(a) (b)

Figure 7 Monte Carlo a) PBP and b) PI

The Monte Carlo simulation result for PBP is a maximum value of 2.31 years. This result is considered good because the payback period is quite short. The minimum PI is 3.38. It is concluded that the plant in this research has minimal risk in terms of PI. Overall, the Monte Carlo simulation results for NPV, IRR, PBP, and PI show good results, all showing positive values.

Next, sensitivity analysis is performed to see which variables most affect the economic parameters (NPV, IRR, PBP, and PI). The sensitivity analysis results can be seen in Figures 8, 9, 10, and 11 where orange line is DME selling price, blue line is raw material price, and red line is catalyst price.

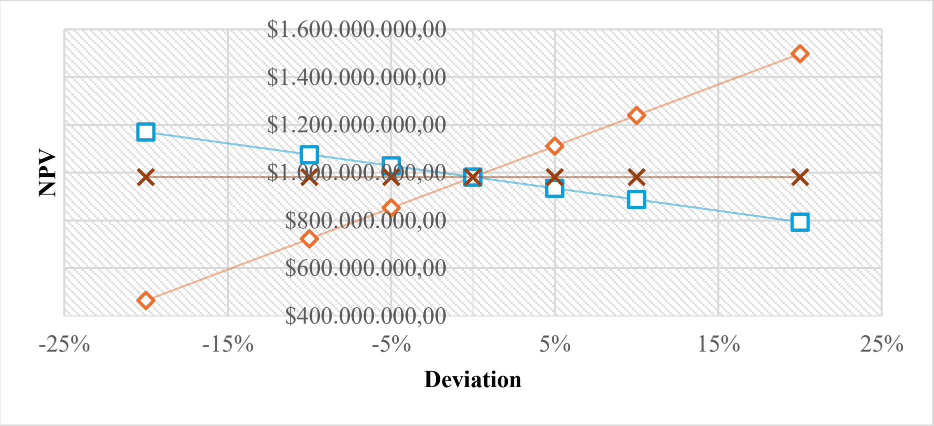


Figure 8 NPV Fluctuation Graph

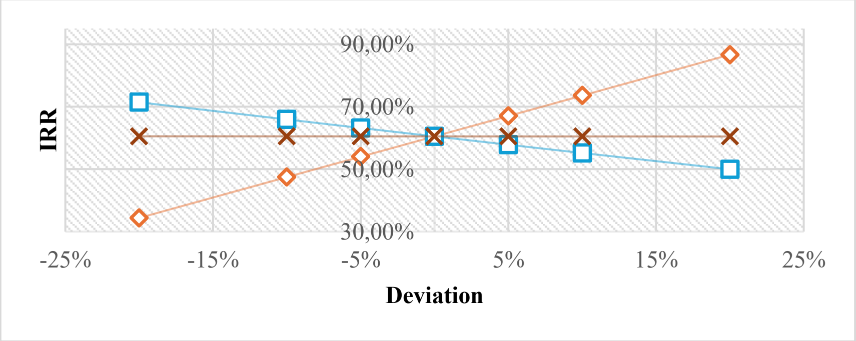


Figure 9 IRR Fluctuation Graph

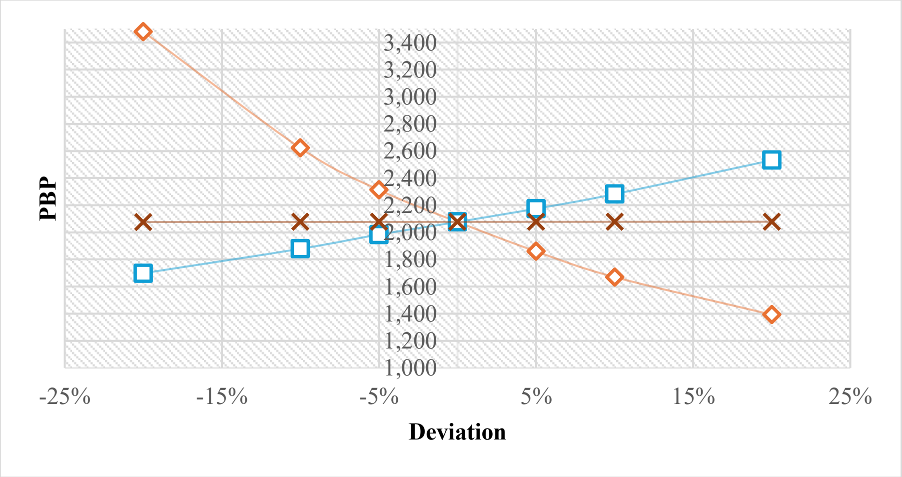


Figure 10 PBP Fluctuation Graph

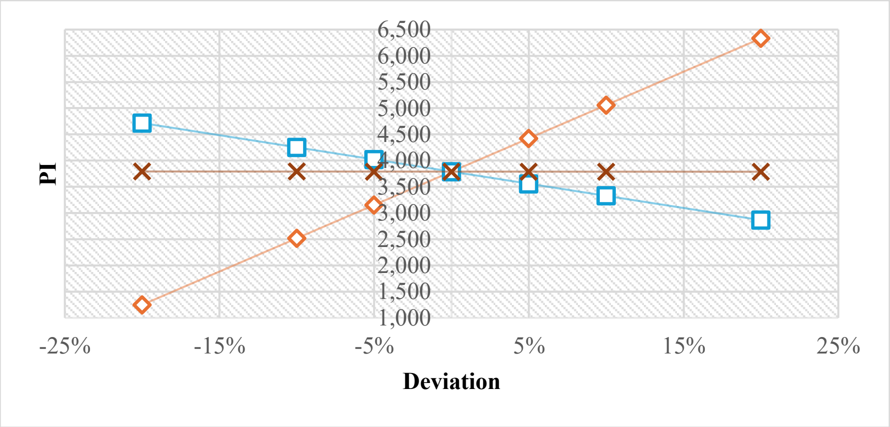


Figure 11 PI Fluctuation Graph

Figure 8 shows that DME price has the greatest influence on NPV, remaining positive even when decreased by 20%. Figure 9 shows DME price affects IRR, remaining above 30%. Figure 10 shows DME price affects PBP, remaining below 3.5 years. Figure 11 shows DME price affects PI, remaining above 1, so it is still feasible for investment.

CONCLUSION

This study confirms the technical and economic feasibility of producing high-purity (99.97%) *Dimethyl Ether* (*DME*) from CO_2 and CH_4 via dry methane reforming and direct synthesis, achieving a daily output of 1,304.91 tons at a market price of $1,300 per ton. The project demonstrates strong financial metrics, including a Net Present Value (*NPV*) of $1.78 billion, an Internal Rate of Return (*IRR*) of 58.44%, a rapid payback period of 2.041 years, and a robust Profitability Index (*PI*) of 3.675, underscoring its commercial viability. Monte Carlo simulations with 1,000 iterations at a 95% confidence level further validate the project's financial resilience, with all key indicators remaining positive and a maximum payback period of 2.31 years, indicating low financial risk and stable returns even under variable conditions. For future research, integrating renewable energy sources into the DME production process is recommended to enhance sustainability and further reduce the carbon footprint. Additionally, exploring alternative catalysts for dry reforming and DME synthesis, conducting more detailed sensitivity analyses on raw material price fluctuations and carbon tax impacts, and performing comparative studies with other green fuel production methods would provide valuable insights to strengthen the long-term economic and environmental positioning of DME in the evolving energy landscape.

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