Journal Majelis Paspama
Volume 4 Number 02, 2026 (No 167-177)
E.SSN 2987-1379 (Online)

Sustainable Profitability Analysis of Natural Gas-Based Methanol Production

Onuoha Fidelis Wopara[1], Nnadikwe Johnson[2]
[1]Petroleum Engineering Department, Rivers State University Port-Harcourt. [2]Centre For Gas Refining And Petrochemical Engineering, University of Port-Harcourt, Rivers State Nigeria

Article Info

Corresponding Author:
Onuoha Fidelis Wopara
E-mail:
wopara.fidelis@ust.edu.ng

ABSTRACT

Methanol production from natural gas is gaining traction as a sustainable alternative to conventional fuels. This paper presents an economic analysis and design of large-scale methanol production, optimizing synthesis gas composition (CO/CO_2 ratio) for enhanced yield. A Maximum Energy Recovery (MER) heat exchanger network reduces operational costs, achieving a break-even point of 2.69 years. Key results include: production capacity meeting ~1% of global demand, total operating cost optimized at 4× raw materials cost, and a fixed-tube sheet heat exchanger (22.54 m^2) selected for low-temperature heat exchange. Sensitivity analyses demonstrate robustness against natural gas price fluctuations and methanol market trends, underscoring the process's economic viability and environmental sustainability.

Keywords:
Profitability, Methanol, Production,Optimization, CO2

INTRODUCTION

The production of methanol from natural gas has gained significant attention in recent years due to its potential as a cleaner-burning fuel and a key feedstock for various industrial processes (Al-Yafei et al., 2025). As the demand for methanol continues to grow, optimizing the production process to achieve sustainable profitability is crucial for industries involved in natural gas conversion. Methanol production is typically achieved through steam reforming of natural gas followed by catalytic conversion to methanol, a process that involves significant energy consumption and greenhouse gas emissions (Blumberg et al., 2017; Deka et al., 2022). Methanol is a vital chemical used in various applications, including fuel production, formaldehyde synthesis, and as a precursor for other chemicals like acetic acid and dimethyl ether (DME) (González-Garay et al., 2019). The sustainability of natural gas-based methanol production has been evaluated in various studies, highlighting the importance of optimizing energy efficiency and minimizing environmental impact (Ren et al., 2023; Bozzano & Manenti, 2016).

SYNGAS PRODUCTION AND PURIFICATION

Steam reforming is a critical step in methanol production, where natural gas reacts with steam over a nickel catalyst to produce syngas (CO and H_2) (Blumberg et al., 2017). However, sulphur compounds in the syngas can poison downstream catalysts, reducing methanol synthesis efficiency (Verhelst et al., 2019). To mitigate this, sulphur is removed through hydrodesulfurization (HDS) and absorption processes.

Methanol Uses and Application

1. Fuel production: Methanol is used as a fuel additive, biodiesel, and gasoline blending component.
2. Formaldehyde production: A key feedstock for producing formaldehyde, used in resins, adhesives, and plastics.
3. Chemical synthesis: Used to produce acetic acid, methyl methacrylate, and other chemicals.
4. Solvents and coatings: Methanol is used in paints, varnishes, and cleaning agents.
5. Plastic production: Used in producing polyethylene terephthalate (PET) and other plastics.
6. Energy storage: Methanol can be used as a fuel cell energy source or for hydrogen storage.
7. Antifreeze and coolant: Used in windshield washer fluids and as an antifreeze agent

Methanol Manufacturing Process

Methanol is typically produced through a multi-step process involving natural gas conversion:

1. Natural gas (mainly methane) is converted to syngas (CO, CO_2, H_2)
2. Syngas is catalytically converted to methanol (CH_3OH)
3. Methanol is then purified through distillation

In the production of methanol from natural gas, synthesis gas (syngas) is generated through steam reforming. This process involves the reaction of water and natural gas (primarily methane) over a nickel catalyst at high temperatures (approximately 800°C) to produce hydrogen and carbon monoxide:

$$CH_4(g) + H_2O(g) Ni/800^{\circ}C \Leftrightarrow C\ O(g) + 3H_2(g)$$

This syngas is a crucial intermediate in the sustainable production of methanol, impacting the overall profitability and environmental footprint of natural gas-based methanol production. In conjunction with steam reforming, the water-gas shift (WGS) reaction occurs, influencing the syngas composition critical for methanol synthesis. The WGS reaction involves steam reacting with carbon monoxide to form carbon dioxide.

$$CO(g) + H_2O(g) Ni/800^{\circ}C \Leftrightarrow C\ O_2(g) + H_2(g)$$

Optimizing the CO/CO_2 ratio is essential, as methanol synthesis primarily utilizes CO. Managing this balance is crucial for maximizing methanol yield and improving the sustainable profitability of natural gas-based methanol production, as excess CO_2 may require conversion back to CO via reverse WGS reaction Sulphur compounds in the syngas post-steam reforming can poison downstream catalysts, reducing methanol synthesis efficiency. To mitigate this, sulphur is removed through hydrodesulfurization (HDS) where syngas reacts with H_2 over a cobalt-molybdenum catalyst at 400°C, converting sulphur compounds to H_2S:

$H_2(g) + S\ H_2S(g)$

H_2S is then captured by zinc oxide, forming zinc sulphide:

$H_2S(g) + ZnO(s)$ ----$ZnS(s) + H_2O(g)$

This sulphur removal is critical for protecting catalysts and optimizing methanol yield, directly impacting the sustainable profitability of natural gas-based methanol production.

The syngas is compressed and fed into a methanol synthesis reactor, where it undergoes a catalytic reaction over a copper-zinc catalyst to produce methanol.

$$2H_2(g) + CO(g) 5MPa/270℃/CuO \Leftrightarrow CH_3OH(l)$$

This exothermic reaction generates significant heat, which is recovered to produce steam for use in the steam reforming process, enhancing overall energy efficiency (Bozzano & Manenti, 2016; Ren et al., 2023). Optimizing this heat integration is crucial for improving the sustainable profitability of natural gas-based methanol production.

A three-step distillation process is employed to purify methanol, comprising an extraction column, refining column, and recovery column. Volatile impurities (e.g., CO2, CO) and dissolved gases are removed in the extraction column. High-purity methanol is obtained from the top of the refining column. The recovery column further separates methanol from heavier alcohols like ethanol, enhancing overall process efficiency. This distillation sequence is critical for achieving high-purity methanol, directly impacting the product's market value and the process's sustainable profitability (González-Garay et al., 2019; Deka et al., 2022)

Economic Potential Calculation

To evaluate the sustainable profitability of natural gas-based methanol production, we'll calculate key economic indicators. Let's break it down:

1. Methanol Production Cost: Estimated at $300-500 per ton (Deka et al., 2022)
2. Methanol Selling Price: Around $400-600 per ton (Methanol Institute, 2022)
3. Natural Gas Feedstock Cost: Major contributor to production cost (~60-70%)
4. Energy Efficiency: Crucial for reducing operational costs and environmental impact

Key metrics

a. Gross Profit Margin: (Selling Price - Production Cost) / Selling Price
b. Payback Period: Depends on capital investment, production scale, and methanol price

Table 1: Global Prices of Raw Materials and End Products

Item	Price ($/kg)
Methanol	0.393
Natural -Gas	0 .202
Water	Negligible
Hydrogen	1.9

$CH_4(g) + H_2O(g) \rightarrow CH_3OH(l) + H_2(g)$

The overall economic potential (EP) as a function of conversion X is given by:

EP = 32_0.393_X + 2_1.9_X - 16_0.202_(1-X)

EP = 19.456X - 3.232

This equation represents the economic potential of the methanol production process, considering the conversion X in the reactor. To ensure process viability, a minimum conversion of 16.56% is required. The water-methanol separation via distillation is straightforward due to a relative volatility of 4.54 at room temperature (Bozzano & Manenti, 2016). This continuous process is favored for its cost-effective catalysts and adaptability. Natural gas, being readily available and easily transportable, enhances process feasibility. With conversion rates reaching up to 90% (Olah et al., 2009), the process yields a promising economic potential of $14.30/kg of methanol.

Process Schematic

Water and natural gas are fed into the reformer, producing syngas (CO, CO2, H2). The reactor effluent (Stream 5) is mixed with recycled unreacted gases (Stream 14) and fed into the methanol synthesis reactor. The reactor product (Stream 9) is flashed to separate gases (recycled) from liquid products. The liquid mixture (water, methanol) is distilled, leveraging a relative volatility of 4.54, to produce high-purity methanol. Optimizing the CO:CO2 ratio in the reformer is crucial for maximizing methanol yield and process efficiency, directly impacting sustainable profitability.

A process flow diagram has been developed based on the described reactions and process steps

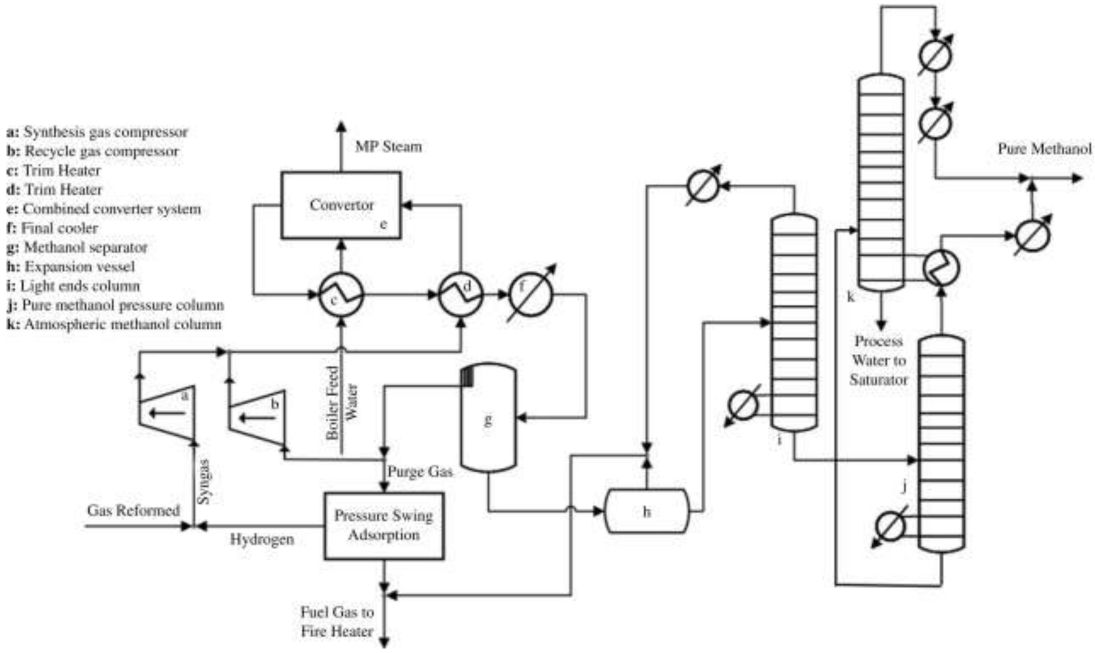

Fig. 1: Methanol Production Process Flow Schematic

Design Parameters

To meet the global methanol demand, the process is designed to produce 0.65 million metric tons per annum, targeting 1% of the global market share (Methanol Institute, 2022). This production capacity serves as the basis for mass balance calculations, evaluating the sustainable profitability of natural gas-based methanol production, while ensuring efficient resource allocation and process optimization. The process design assumes ideal separation in the flash drum and distillation column for initial simplicity. The steam reformer operates at 10-80 bar, 700°C, with Ni catalyst, facilitating methanol synthesis and water-gas shift reactions. The Soave-Redlich-Kwong equation of state models non-ideal gas behavior, ensuring accurate thermodynamic predictions (Smith et al., 2018). Natural gas composition: 95% methane, 3% ethane, and higher hydrocarbons, with a 3:1 steam-to-carbon ratio. These conditions aim to optimize methanol yield and energy efficiency, enhancing the sustainable profitability of natural gas-based methanol production. The equilibrium expression for methanol synthesis is given by:

$$KP1 = (yCH_3OH) / (yCO \times yH_2{}^2)$$

This equation represents the equilibrium constant for methanol synthesis, crucial for optimizing reaction conditions and process efficiency in natural gas-based methanol production.

$$KP2 = (yCO_2 \times yH2) / (yCO \times yH_2O)$$

This expression represents the water-gas shift reaction equilibrium, influencing overall process efficiency and methanol yield in natural gas-based production. To optimize methanol production, process conditions should favor CO formation while maintaining high selectivity. The water-gas shift reaction is minimized to maximize CO availability for methanol synthesis. With Ni catalyst, selectivity ranges 60-70% across various temperatures, impacting overall process efficiency and profitability.

Process Optimization Strategy:

a. Minimize water-gas shift reaction rate
b. Maximize CO formation for methanol synthesis
c. Leverage Ni catalyst selectivity (60-70%)

Material Balance Basis

Methanol production: 0.65 million metric tons/year

a. CO conversion: 64%
b. CO_2 conversion: 17%
c. Selectivity: >60% (Ni catalyst)

These assumptions enable calculation of reactant requirements and process streams, assessing sustainable profitability of natural gas-based methanol production.

Given:- Methanol production = 0.65 million metric tons/year = 650,000 tons/year

a. CO conversion = 64%
b. CO_2 conversion = 17%
c. Reaction: $CO + 2H_2 \rightarrow CH_3OH$ (main reaction)

Stoichiometry:1 mol CO : 2 mol H_2 : 1 mol CH_3OH

Calculations:

1. Moles of methanol produced
   650,000 tons/year × (1000 kg/ton) / (32 kg/kmol) ≈ 20,312.5 kmol/h
2. Required CO feed
   CO feed = (20,312.5 kmol/h) / 0.64 ≈ 31,738 kmol/h
3. Required H_2 feed
   H_2 feed = 2 × (20,312.5 kmol/h) / 0.64 ≈ 63,476 kmol/h

Reactor Conditions

a. Temperature: 838.74°C
b. Catalyst: Cu/ZnO
c. Feed ratio: $1.8 < (H_2 - CO_2) / (CO + CO_2) < 2.2$
d. Conversions: CO (64%), CO_2 (17%)

Feed Composition

$H_2:CO:CO_2$ = 100:100:100 moles/h (assumed basis)
- Methane (X moles/h) in feed

Reactions

1. $CO + 2H_2 \rightarrow CH_3OH$
2. $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

These conditions impact methanol yield and process efficiency, influencing sustainable profitability.

Reactor output based on given conversions.

Reactor Output Calculation

1. CO conversion: 64%
2. CO_2 conversion: 17%
3. Feed: $H_2:CO:CO_2$ = 100:100:100 moles/h

Output (moles/h):

a. Co: 100 × (1-0.64) = 36
b. Co_2: 100 × (1-0.17) = 83

c. H_2: 100 - (2×64 + 3×17) = -31 (Limiting Reactant, Adjust)
d. Ch_3Oh: 64 (From Co) + 17 (From Co_2) = 81
e. H_2O: 17 (from CO_2 reaction)

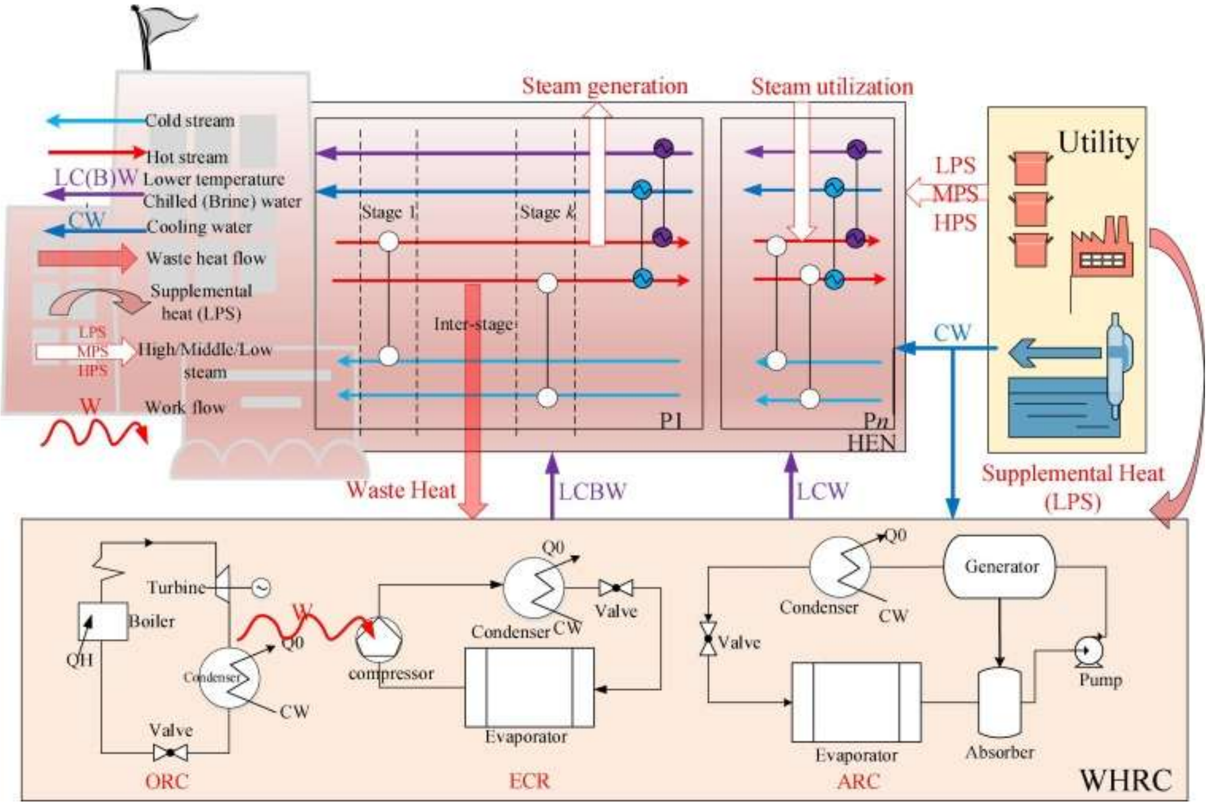

Figure 2: Heat-integrated process flow diagram

Table 2: Initial component mole fractions

Components	Mole fraction
CH_4	0.16
CO_2	0.07
CO	0.23
H_2	0.54

Analysis of Initial Component Mole Fractions

The feed composition (Table 2) shows:

a. CH_4 (0.16): Natural gas is the primary feedstock. Its conversion affects methanol yield and process efficiency.
b. CO_2 (0.07): Contributes to methanol synthesis via CO_2 hydrogenation, impacting carbon utilization.
c. CO (0.23): Key reactant for methanol production. Its ratio with H_2 influences conversion and selectivity.
d. H_2 (0.54): Primary hydrogen source drives methanol synthesis reactions

Flow Rates Based on Final Parameters

a. Temperature: 838.74°C
b. Methane conversion: 85%
c. Water-gas shift Keq: 1.05
d. Feed composition (mole fractions):
    1. CH_4: 0.16

2. CO_2: 0.07
3. CO: 0.23
4. H_2: 0.54

These parameters influence product flow rates and process efficiency.

Table 3: Final component flow rates for the plant

Stream	Flow Rate (kmol/hr)
INPUTS-PROCESS	
H_2O	9431.85
CH_4	8130.87
OUTPUTS-PROCESS	
H_20(Products)	106.84
Methanol	2318.76
Purge	1079.42
CH_4	439.24
Hydrogen	509.54
CO	92.10
CO_2	38.65
Recycle:	**13797.88**
CH_4	5492.24
Hydrogen	6370.86
CO	151.87
CO_2	482.87
Synthesis Gas:	**9565.68**
CO_2	573.88
CO	2295.80
CH_4	1434.81
Hydrogen	5261.21

Table 3: Final Component Flow Rates

a. Shows inputs, outputs, recycle, and synthesis gas streams
b. Key for understanding methanol production efficiency
c. Impacts profitability and sustainability

Distillation Column Design

a. Separation Method: Distillation column using McCabe-Thiele method
b. Calculation Tool: MATLAB
c. Result: 7 theoretical stages required

HEAT RECOVERY AND OPTIMIZATION

Heat Integration for Sustainable Methanol Production

a. Streams with enthalpy and Cp values:
b. Utilized reactor heat (exothermic reaction) to preheat incoming streams (Stream 5)
c. ΔT_{min} = 10 °C for efficient heat exchange
d. 1 °C loss in reactor cooling jacket

Implications for Sustainability and Profitability

a. Heat recovery boosts energy efficiency and reduces costs
b. Effective heat integration enhances process sustainability
c. Optimizes energy usage in natural gas-based methanol production

Pinch Analysis Results

Pinch Temperatures:

a. Tcold pinch = 240 °C
b. Thot pinch = 250 °C

Minimum Utilities:

a. Qc min = 143.76 MW (cooling)
b. QH min = 9.36 MW (heating)

Design:

a. No loops in heat exchange network
b. Design meets minimum energy requirements

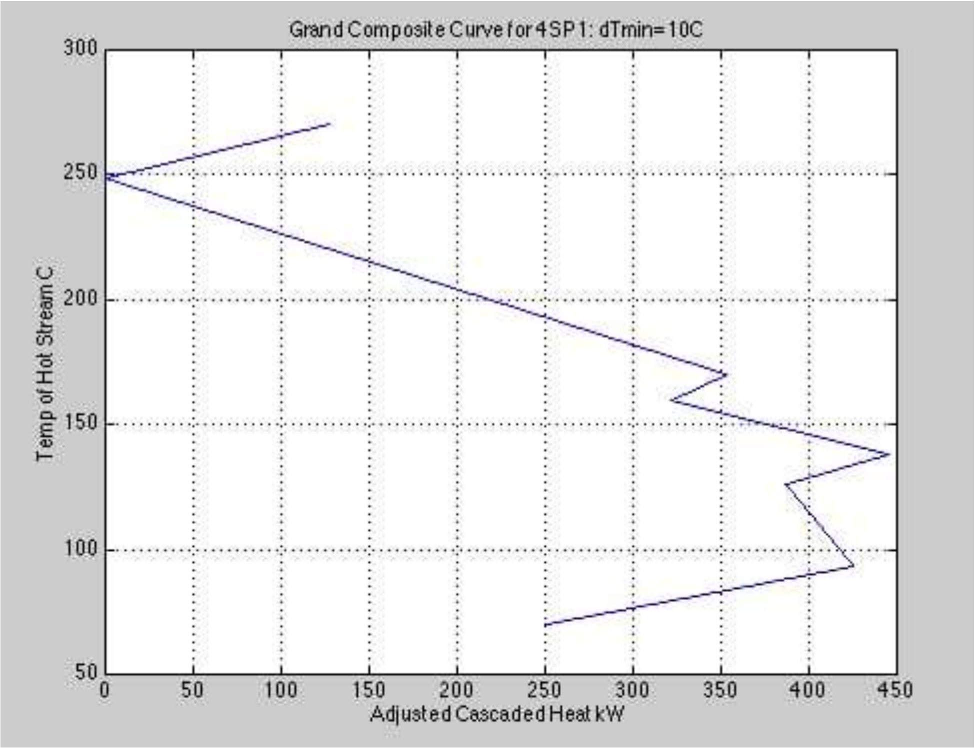

Figure 3: Grand Composite Curve

Sustainable Profitability Analysis.

Process Economics for Sustainable Methanol Production

a. Net Installation Cost: ∑ (Base Cost/Purchase Cost × Multiplier)
b. Purpose: Estimate total installed cost of equipment for economic evaluation

Impact on Sustainability and Profitability:

a. Accurate cost estimation supports investment decisions
b. Influences overall profitability and sustainability of methanol production.

Table 4: Equipment Cost Summary

No.	Name of Equipment	Net Installation Cost ($)	Purchase Cost ($)	Multiplier
1	Distillation Column	137,758	65,400	2.1
2	2 Reactors	347,120.9	182,693.8	1.8
3	9 Heat Exchangers	560,690	294,900	1.9

Total Onsite Cost for Methanol Production

a. Total Installation Cost: $1,045,568.9
b. Equipment:
   1. Distillation Column: $137,758
   2. Reactors: $347,120.9
   3. 9 Heat Exchangers: $560,69

Implication: Net Investment impacts profitability and sustainability of natural gas-based methanol production

Raw Materials Cost

Table 5: Costs of Raw Materials

Raw Material	Product	Revenue ($/hr)	Raw Materials Cost ($)	Net Revenue ($/hr)	otal Operating Cost ($/hr
Methane	Methanol	103,309.23	26,148.88	1,046,43.3	104,595.1
	Hydrogen	1,334.222			

Sustainable Profitability Analysis

a. Total Operating Cost: 4 × Raw Materials Cost
b. Profit:
   1. $47.883/hr
   2. $419,455.08/yr
c. Break-Even Analysis:
   1. Interest Rate: 10%
   2. Break-Even Point: 2.69 years

Tube-and-Shell Heat Exchanger

a. Overall Heat Transfer Coefficient (U): 30 W/(m²K)
b. Area (A) Calculation: $A = Q / (U \times \Delta T\_LMTD)$
c. Purpose: Determine heat exchanger size for sustainable methanol production

Table 6: Heat Exchanger Selection

Q (MW)	22.93
T1(C)	28
T2(C)	201.46
T3(C)	260
T4(C)	259
$\Delta TLMTD$(C)	33.87

a. Area (A): 22.54 m²
b. Type: Fixed Tube Sheet Shell and Tube Heat Exchanger
c. Reason: Suitable for low-temperature heat exchange with minimal temperature difference

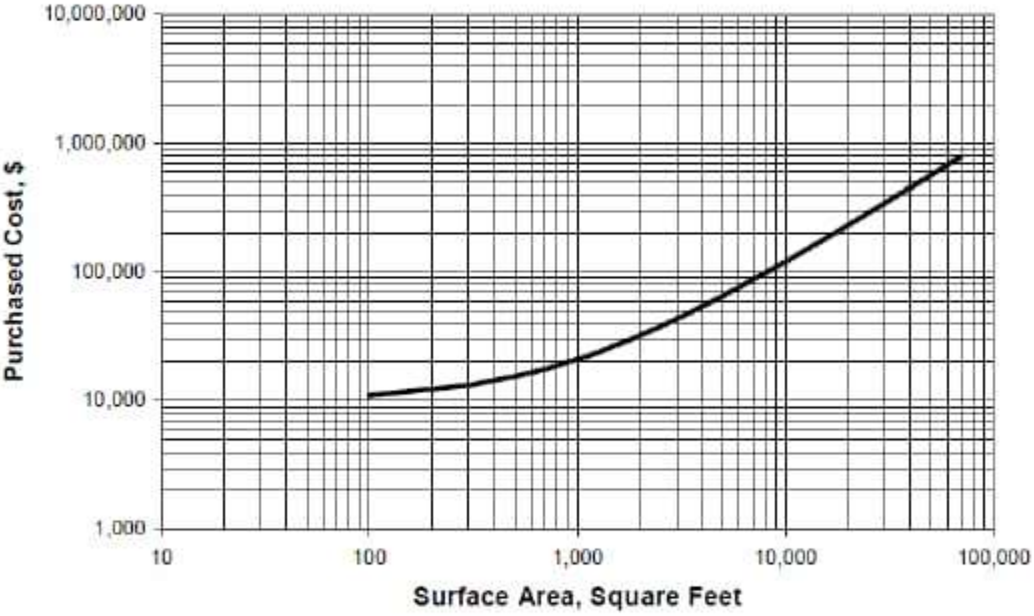

Figure 4: Shell and Tube Heat Exchanger Costs

Heat Exchanger Costs

a. Calculated Area (A): 22.54 m^2
b. Cost Correlation: $C_B = \exp\{11.0545 - 0.9228[\ln(A)] + 0.09861[\ln(A)]^2\}$
c. Cost (C_B): $20,289.48

CONCLUSION

This study presents a sustainable profitability analysis of natural gas-based methanol production, demonstrating a design that caters to approximately 1% of global methanol demand. The total investment required for the plant was estimated empirically, encompassing equipment costs and installations, excluding land costs which appreciate over time. Based on this analysis, the break-even point for the plant is approximately 2.69 years, aligning with industry benchmarks. Notably, the process leverages a Maximum Energy Recovery (MER) designed heat exchanger network, enhancing cost efficiency. Sensitivity analyses indicate robustness in profitability under varying natural gas prices and methanol market fluctuations. The findings underscore the economic viability and environmental sustainability of natural gas-based methanol production, positioning it as a promising alternative to conventional fossil fuels. This research contributes to the ongoing discourse on sustainable chemical production and provides a framework for evaluating similar projects. Future work could explore optimizing feedstock diversification and integrating renewable energy sources to further enhance sustainability

REFERENCES

1. Al-Yafei, H., Aseel, S., & Kunju, A. A. (2025). Evaluating the Sustainability of the Natural Gas-Based Methanol-to-Gasoline Industry: A Global Systematic Review. Sustainability, 17(12), 5355. (link unavailable)
2. Blumberg, T., Morosuk, T., & Tsatsaronis, G. (2017). Exergy-based evaluation of methanol production from natural gas with CO2 utilization. Energy, 141, 2528–2539. (link unavailable)

3. Deka, T. J., Osman, A. I., Baruah, D. C., & Rooney, D. W. (2022). Methanol fuel production, utilization, and techno-economy: A review. Environmental Chemistry Letters, 20(6), 3525–3554. (link unavailable)
4. González-Garay, A., Frei, M. S., Al-Qahtani, A., Mondelli, C., & Guillén-Gosálbez, G. (2019). Plant-to-planet analysis of CO2-based methanol processes. Energy & Environmental Science, 12(12), 3425–3436. (link unavailable)
5. Ren, B.-P., Xu, Y.-P., Huang, Y.-W., She, C., & Sun, B. (2023). Methanol production from natural gas reforming and CO2 capturing process, simulation, design, and technical-economic analysis. Energy, 263, 125879. (link unavailable)
6. Bozzano, G., & Manenti, F. (2016). Efficient methanol synthesis: Perspectives, technologies and optimization strategies. Progress in Energy and Combustion Science, 56, 71–105. (link unavailable)
7. Verhelst, S., Turner, J. W. G., Sileghem, L., & Vancoillie, J. (2019). Methanol as a fuel for internal combustion engines. Progress in Energy and Combustion Science, 70, 43–88. (link unavailable)
8. Chen, Z., Shen, Q., Sun, N., & Wei, W. (2019). Life cycle assessment of typical methanol production routes: The environmental impacts analysis and power optimization. Journal of Cleaner Production, 220, 408–416. (link unavailable)
9. Bazaluk, O., Havrysh, V., Nitsenko, V., Baležentis, T., Streimikiene, D., & Tarkhanova, E. A. (2020). Assessment of Green Methanol Production Potential and Related Economic and Environmental Benefits: The Case of China. Energies, 13(12), 3113. (link unavailable)
10. Olah, G. A., Goeppert, A., & Prakash, G. K. S. (2009). Beyond oil and gas: The methanol economy. ECS Transactions, 35(1), 31–40. (link unavailable)
11. Nichols, R. J. (2003). The methanol story: A sustainable fuel for the future. Science and Industrial Research, 62(1-2), 97–105.
12. Tabibian, S. S., & Sharifzadeh, M. (2023). Statistical and analytical investigation of methanol applications, production technologies, value-chain and economy with a special focus on renewable methanol. Renewable and Sustainable Energy Reviews, 179, 113281. (link unavailable)
13. Methanol Institute. (2022). Carbon Footprint of Methanol.