



# Techno-Economic and Sensitivity Analysis of Natural Gas Liquefaction Using the Propane Pre-Cooled Mixed Refrigerant (C3MR) Cycle

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## ABSTRACT

Liquefied natural gas (LNG) is essential in the global energy transition because it allows for long-distance transportation of natural gas with reduced emissions. Improving the energy efficiency and economic feasibility of LNG liquefaction processes is therefore important. This study offers a comprehensive techno-economic analysis and sensitivity evaluation of natural gas liquefaction using the Propane Pre-Cooled Mixed Refrigerant (C3MR) cycle. A steady-state simulation was developed in Aspen HYSYS V12, utilizing the Peng-Robinson equation of state to accurately model the cryogenic behavior of multicomponent streams. The process was segmented into two integrated subsystems: propane precooling and mixed refrigerant subcooling, with performance measured through key indicators such as energy use, power requirements, and indirect CO<sub>2</sub> emissions.

The results show that although the MR cycle uses slightly more electrical power than the propane precooling stage, it leads to lower overall energy use, less cooling water requirement, and significantly fewer environmental emissions. From an economic standpoint, cost estimates based on updated CEPCI indices indicate that these technical improvements result in strong financial performance, marked by high profitability and a quick payback period under typical LNG market conditions. Sensitivity analysis also indicates that higher natural gas feed rates, moderate refrigerant flow rates, and an inlet pressure near 65 bar best balance energy efficiency with economic return. Overall, the findings confirm that the C3MR cycle is a solid and practical option for large-scale LNG production, effectively connecting better thermodynamic performance with positive economic results.

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## 1. Introduction

Natural gas is increasingly recognized as a key transitional energy source due to its relatively low carbon intensity compared with other fossil fuels, and liquefied natural gas (LNG) has become central to enabling efficient long-distance energy transport and supporting the transition towards lower-emission energy systems (Zhao et al. 2024; Wang et al. 2025). Its flexibility in power generation, industrial use, and transport, along with the growth of LNG infrastructure, makes it a key bridge between conventional and renewable energy systems. (Ghasemzadeh et al. 2017; Jafari et al. 2020b; Jafari and Garakani 2021). The liquefaction process reduces the volume of natural gas by approximately 600 times, enabling cost-effective transportation over long distances, particularly via marine routes (Falsafi et al. 2024). However, this phase change is both thermodynamically and economically intensive (Yuan et al. 2024). Typically, the refrigeration and liquefaction stages consume nearly half of the total energy input and account for more than one-third of the capital investment in modern LNG facilities. Therefore, improving the energy and cost efficiency of this process is essential for enhancing the competitiveness of natural gas in a low-carbon future (Balcombe et al. 2021).

Among the various process configurations available, the propane pre-cooled mixed refrigerant cycle, known as the C3MR process, has become the industrial benchmark for large-scale LNG production (Sleiti and Al-Ammari 2023). This process combines a propane-based precooling system with a mixed refrigerant loop to closely match the natural gas cooling curve at each stage of liquefaction (Ahmed et al. 2024). Its strong thermodynamic performance, modular architecture, and industrial maturity are the main reasons behind its widespread deployment in major LNG terminals worldwide. Despite its advantages, the performance of the C3MR cycle

is susceptible to operational variables, including refrigerant composition, compressor pressure levels, and heat exchanger thermal performance (Cui et al. 2024). As a result, achieving stable, efficient operation across a range of conditions requires detailed, multidimensional evaluations (Almeida-Trasvina and Smith 2023).

In recent years, significant research efforts have been devoted to improving the performance of LNG liquefaction systems through advanced process simulation, optimization, and exergy-based analysis. Alabdulkarem et al. (2011) developed a detailed Aspen HYSYS model of the C3MR process and demonstrated that integrating expansion energy recovery could reduce specific power consumption by approximately seven percent. Sanavandi and Ziabasharhagh (2016) further showed that optimization of refrigerant composition and compressor pressure levels leads to measurable reductions in overall energy consumption.

Beyond conventional thermodynamic optimization, several studies have applied advanced exergy and exergoeconomic frameworks to LNG processes. Vatani et al. (2014) conducted a comparative energy and exergy analysis of five industrial liquefaction cycles and identified mixed refrigerant-based configurations as the most energy efficient. Their results showed that operational parameters, particularly compressor pressure ratios, exert a greater influence on system performance than structural modifications. In a subsequent study, Palizdar et al. (2019) performed an exergoeconomic assessment of a nitrogen dual expander LNG process and demonstrated that compressors and expanders account for a significant share of avoidable exergy destruction costs, indicating strong potential for cost reduction through targeted operational optimization.

More recent high-impact studies have extended these analyses by incorporating multi-objective optimization and advanced

decision-making frameworks. Primabudi et al. (2019) applied a combined exergy and economic optimization approach to the C3MR cycle and reported Pareto optimal trade-offs between energy efficiency and total product cost. Similarly, Shady et al. (2024) employed knowledge-based and constrained Bayesian optimization techniques to improve the operational performance of a large-scale C3MR LNG process, achieving simultaneous reductions in energy consumption and carbon emissions.

Although there has been extensive research on C3MR-based LNG liquefaction, several limitations remain in the current literature. Most earlier studies focus on steady-state thermodynamic analysis or single-objective optimization, often emphasizing energy efficiency or exergy indicators. In many cases, economic factors are analyzed separately or only reported at specific optimal design points. Furthermore, the combined effects of key operating variables such as natural gas throughput, refrigerant circulation rates, compressor pressure levels, and heat exchanger performance on both energy consumption and LNG production costs have not been thoroughly examined. This limited integration of process analysis and economic evaluation reduces the practical usefulness of many simulation-based studies for industrial design and investment decisions.

To address these issues, this study develops a comprehensive steady-state simulation of the C3MR liquefaction process using Aspen HYSYS and performs an integrated techno-economic and sensitivity analysis. The analysis explores how changes in propane precooling conditions and mixed refrigerant operating parameters influence not only technical metrics, such as specific energy consumption, power demand, and indirect CO<sub>2</sub> emissions, but also key economic indicators like capital cost, payback period, return on investment, and net profit. The main goal is to determine operational

ranges that are both technically feasible and economically viable under conditions typical of industrial LNG plants. By directly connecting process sensitivity to economic performance, this work offers a practical framework to support informed operational optimization and investment decisions for large-scale LNG facilities employing the C3MR cycle.

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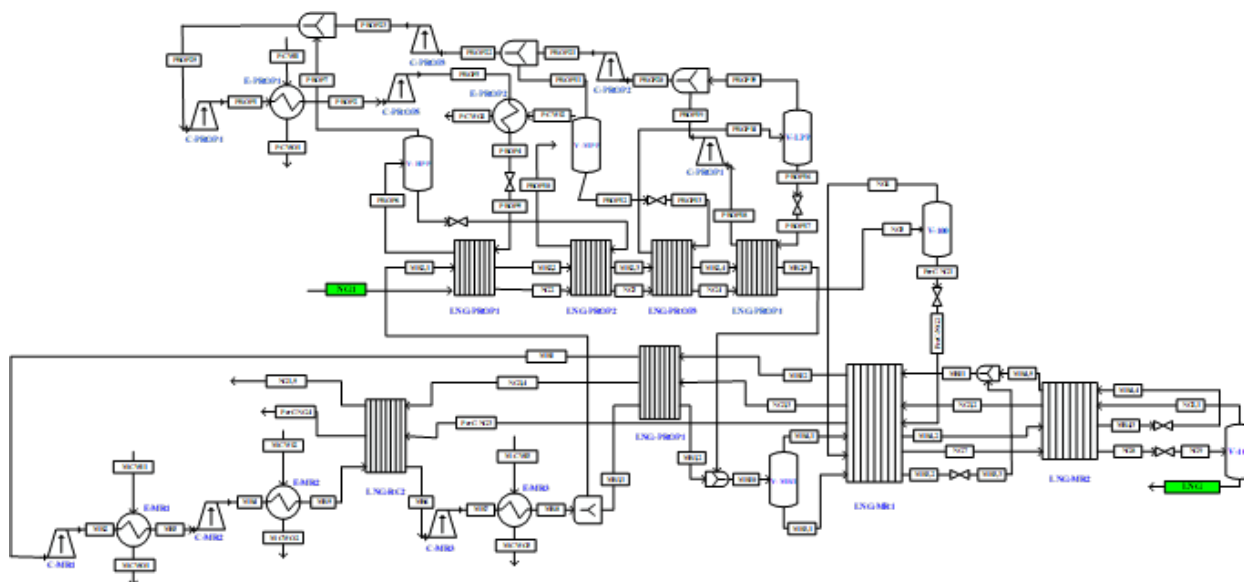
## 2. Methodologies

### 2.1. Simulation Framework and Process Configuration

Process simulation serves as a key tool for accurately analyzing thermodynamic behavior and evaluating various operating scenarios, thereby accelerating the achievement of design and optimization objectives (Jafari et al. 2023; Jafari et al. 2024b; Khosravi et al. 2025). In this study, a detailed simulation of the Propane Pre-cooled Mixed Refrigerant (C3MR) liquefaction process is carried out using Aspen HYSYS V12, a widely used commercial software for modeling cryogenic and hydrocarbon systems. The simulation is performed based on the Peng-Robinson equation of state (PR-EOS), which is well-suited for handling multi-component natural gas and hydrocarbon mixtures under high-pressure and low-temperature conditions (Jafari et al. 2020a; Jafari et al. 2021b; Jafari et al. 2021a; Jafari and Khalili-Garakani 2021). This thermodynamic model accurately predicts the vapor-liquid equilibrium, enthalpy, and density across all stages of the liquefaction cycle. The C3MR process is recognized as one of the most efficient and commonly implemented LNG technologies, accounting for nearly 77% of global LNG production capacity (Hajji et al. 2019). The cycle includes two integrated refrigeration loops: a propane-based precooling cycle and a mixed refrigerant subcooling cycle. The combination of these two stages allows close thermal matching with the natural gas stream and ensures effective precooling, liquefaction, and subcooling of the product.

As shown in (Figure 1), the simulation model replicates the whole sequence of cooling operations from feed gas preprocessing to final LNG production (Hajji et al. 2019). The natural gas stream (NG1) enters the first heat

exchanger (LNG-PROP1) at 25 °C and 6500 kPa and is precooled across four sequential exchangers (LNG-PROP1 to LNG-PROP4) to reach -41 °C while maintaining the same pressure.



**Figure 1. Schematic of Natural Gas Liquefaction Using the C3MR Process with Sequential Propane Precooling (Hajji et al. 2019)**

The propane refrigerant cycle is designed to operate at four evaporation pressure levels, each corresponding to one of the precooling stages. Evaporated propane from each exchanger is routed to three two-phase separators (V-HPP, V-MPP, V-LPP), where it is separated into vapor and liquid fractions. The liquid stream undergoes throttling via Joule-Thomson (J-T) valves (VLV-101, VLV-MPP, VLV-102, VLV-MP) and provides the necessary refrigeration load to the next exchanger stage. Meanwhile, the vapor stream is recompressed to its original pressure through multistage compression and mixing (Hajji et al. 2019).

The mixed refrigerant (MR) cycle manages the subcooling stage. The MR stream is compressed in three steps with compressors C-MR1, C-MR2, and C-MR3, with interstage cooling in between. After compression, the stream enters a tee junction (TEE-100), splitting into two branches.

One branch (MR1 and MR2) joins the propane-cooled precooling section, while the

other continues into the deeper cryogenic stages. The precooled MR then enters separator V-MR1, where it separates into two distinct phases. Each phase passes through additional heat exchangers (LNG-MR1 and LNG-MR2), is throttled by valves (VLV-MR1, VLV-MR2), and is then recombined in MX-MR2 to complete the subcooling loop (Hajji et al. 2019).

After the MR and NG streams are sufficiently cooled, the NG stream passes through valve VLV-NG, enters the final separator V-101, and is withdrawn as liquefied natural gas at -160 °C. The feed compositions for the natural gas and mixed refrigerant (MR) streams, along with their inlet flow rate, pressure, and temperature, are reported in (Table 1) (Hajji et al. 2019).

Natural gas mainly consists of methane with small amounts of ethane and propane. The MR used in this study includes  $\text{CH}_4$ ,  $\text{C}_2\text{H}_6$ ,  $\text{C}_3\text{H}_8$ , and  $\text{N}_2$ , chosen to provide an appropriate temperature glide and better match the natural gas cooling curve in the primary cryogenic heat exchanger.

**Table 1: Feed Conditions for NG, MR, and Propane Streams**

Stream Name	NG1	MR1	PROP1
Vapour Fraction	1.0	1.0	1.0
Temperature (°C)	25.0	-27.7	50.7
Pressure (MPa)	6.5	0.7	0.9
Mass Flow (Ton/h)	360.0	1000.0	1000.0
Mole Frac (CH <sub>4</sub> )	0.86	0.60	0.00
Mole Frac (C <sub>2</sub> H <sub>6</sub> )	0.08	0.20	0.00
Mole Frac (C <sub>3</sub> H <sub>8</sub> )	0.06	0.10	1.00
Mole Frac (N <sub>2</sub> )	0.00	0.10	0.00

## 2.2. Sensitivity Analysis Methodology

To assess the influence of key operating parameters on the technical and economic performance of the C3MR-based LNG liquefaction process, a sensitivity analysis was performed using the Case Study module in Aspen HYSYS (Ghasemzadeh et al. 2016; Jafari et al. 2019). The following four primary variables were selected based on their operational significance and direct impact on refrigeration load, energy consumption, and process economics:

- Natural gas (NG) mass flow rate
- Natural gas (NG) feed pressure
- Mixed refrigerant (MR) mass flow rate
- Propane mass flow rate

Each parameter was systematically varied within an operationally feasible range while monitoring its effect on specific energy consumption (SEC), total power requirement, payback period (PBP), and annual net profit.

The selected ranges for natural gas and refrigerant flow rates were chosen to fully represent typical industrial operating conditions reported for large-scale C3MR-based

LNG plants. These ranges were defined based on practical limitations of compressor capacity, heat exchanger duty, and stable process operation, as well as values commonly reported in industrial case studies and literature. This ensures that the sensitivity analysis remains both technically realistic and directly applicable to industrial LNG operations. The parametric analysis aimed to identify optimal operating conditions and to determine the sensitivity of process performance indicators to changes in these critical variables.

This approach allowed for a precise assessment of scale effects, energy efficiency trends, and economic trade-offs related to each variable, offering practical guidelines for optimizing the overall performance and profitability of the liquefaction process.

## 2.3. Economic Evaluation Methodology

Economic evaluation is a vital component in the design and development of chemical and energy-intensive process systems (Yoon et al. 2025). It enables feasibility assessments, investment planning, and cost-performance comparisons. In this study, the economic analysis was conducted in line with the methodology presented by Towler and Sinnott, beginning with the estimation of capital expenditure (CAPEX), followed by operating costs (OPEX) and profitability metrics such as payback period and return on investment (Bansod et al. 2025; Ghasemzadeh et al. 2025).

All economic calculations were implemented using a spreadsheet-based framework in Microsoft Excel, while the required process data (e.g., compressor power, heat exchanger area, and vessel specifications) were obtained from the Aspen HYSYS process simulation. Commercial economic evaluation tools such as COMFAR or Aspen Economic Analyzer were not used in this study.

The capital investment was estimated by first calculating the purchase cost of major process

equipment. Where possible, cost data were derived from literature and updated using the Chemical Engineering Plant Cost Index (CEPCI). The reference year was 2010, with a CEPCI value of 532.9, and the costs were escalated to 2025 using a CEPCI of 800.2, resulting in an update factor of 1.502 (Jafari et al. 2019; Ghasemzadeh et al. 2025). This cost escalation was performed using the standard cost-index scaling relationship recommended in chemical engineering economic analysis to ensure consistency between the base-year equipment correlations and the economic conditions of the analysis year.

The updated equipment costs were then multiplied by standard installation factors and contingency allowances to derive the Total

Fixed Capital Cost (TFC) and Total Capital Cost (TCC). Key equipment categories included:

- Compressors (reciprocating and centrifugal)
- LNG multi-stream heat exchangers
- Shell-and-tube heat exchangers
- Vertical vessels (separators)

Empirical cost estimation formulas and their related installation factors for major equipment are listed in (Table 2) and were used to calculate the base capital cost of the LNG process units.

The calculated purchase costs were then multiplied by the corresponding installation factors to estimate the installed equipment costs prior to the total capital investment calculation.

**Table 2: Cost Estimation Equations and Installation Factors for Main Process Equipment (Behroozsarand and Ghasemzadeh 2022; Jafari et al. 2024a)**

Equipment Type	Cost Estimation Formula	Installation Factor
Reciprocating Compressor	$C = 260,000 + 2700 \times (\text{Power})^{0.75}$	2.5
Centrifugal Compressor	$C = 580,000 + 20000 \times (\text{Power})^{0.60}$	2.5
LNG Multi-stream Heat Exchanger	$C = 425 \times \text{Area}$	3.5
Shell-and-Tube Heat Exchanger	$C = 28,000 + 54 \times (\text{Area})^{1.2}$	3.5
Vertical Vessel	$C = 11,600 + 34 \times (\text{Mass})^{0.85}$	4

The total capital investment was determined using a structured bottom-up approach by summing the fixed and working capital requirements (Towler and Sinnott 2021). The process began with the Battery Limit Investment, which covers the direct costs of purchasing, installing, and commissioning core process equipment within the plant's defined boundaries. Subsequently, Offsite Costs and General Services were added to account for utilities, infrastructure, and auxiliary facilities essential for safe and reliable operation. Together, these two elements formed the

total direct capital cost (Jafari et al. 2024a). A contingency equal to 25% of the direct capital cost was applied to address uncertainties, such as material price fluctuations and schedule delays, resulting in the TFC (Shahab-Deljoo et al. 2023). The Total Working Capital (TWC) was then estimated to cover initial operational needs, including feedstock, labor, and spare parts during startup. Finally, the TCC was calculated by adding TFC and TWC, reflecting the overall investment required for project implementation and startup (Jafari et al. 2021b).

The primary variable operating costs, including natural gas feedstock, electric power, and cooling water, were estimated on a per-ton basis of LNG production, as shown in (Table 3). These utility costs were applied based on the specific energy and utility consumption rates obtained from the Aspen HYSYS simulation results for the LNG process.

In addition, labor costs were calculated based on a two-shift operational schedule, assuming an hourly wage rate of \$60 (Zhai et al. 2025). Depreciation was estimated at 10% of the total fixed capital investment on an annual basis. Overhead expenses, insurance, and depreciation were then incorporated into the calculation of the plant gate cost (Stewart and Shirvan 2022). Furthermore, general and administrative expenditures, along with return-on-investment expectations, were taken into account to estimate the required product selling price (Fikri 2018).

**Table 3: Cost Estimation Equations for Variable Operating Expenses (Towler and Sinnott 2021)**

Unit Cost	Value	Unit
NG Cost	3.20	USD/MMBTU
Power Cost	0.10	USD/KWh
Cooling Water Cost	0.22	USD/MMBTU

The production cost and gross profit margin were calculated using a stepwise cost aggregation approach (Yu et al. 2026). The process began with estimating variable costs, including natural gas feedstock, electricity, and cooling water, all reported per ton of LNG. Direct labor costs were then added, based on assumed operator and maintenance wages under a two-shift schedule. Additional elements such as laboratory staffing, maintenance materials, and operating supplies were also included. These items together formed the total direct cost. Plant overheads were then incorporated

as a fixed percentage of total labor cost, along with taxes and insurance, estimated relative to the fixed capital cost. This resulted in the plant's cash cost. Depreciation was added next, typically set at 10% of total fixed capital, to obtain the plant gate cost (Khan et al. 2023). This figure reflects the full cost of producing and delivering one ton of LNG. Further costs, such as general and administrative expenses, sales, research, and the targeted return on investment, were included to calculate the required product value or breakeven selling price. The gross profit margin was finally evaluated by comparing this value with the current LNG market price, calculating the difference, and expressing it as a percentage of the market price.

## 2.4. Technical Performance

To assess the technical performance of the LNG liquefaction system in detail, the process was divided into two distinct operational subsystems. The first is the precooling section, where pure propane is used to reduce the temperature of the natural gas and a portion of the mixed refrigerant. The second section is the liquefaction and subcooling section, which uses a mixed refrigerant (MR) cycle to achieve the final cryogenic conditions required for LNG production. This structural division enables a more focused evaluation of energy use, utility demand, and indirect environmental impacts in each section of the process. A set of Key Performance Indicators (KPIs) was employed to quantify and compare the technical behavior of both subsystems. These indicators were normalized per kilogram of LNG to facilitate meaningful comparisons. The definitions and calculation formulas for these KPIs are presented in (Table 4). This indicator-based analysis helps identify energy-intensive components of the process and supports informed decisions for future design optimization and energy efficiency improvements.

**Table 4: Definition of Technical Performance Indicators for the Propane Precooling and Mixed Refrigerant Sections (Jafari et al. 2024a)**

Parameter	Unit	Equation
Electricity requirement (ER)	kWh/kg	$ER = \frac{\dot{e}_E}{\dot{m}_{LNG}}$
Cooling Water requirement (CWR)	kWh/kg	$FR = \frac{\dot{e}_F}{\dot{m}_{LNG}}$
Overall energy consumption	kWh/kg	$OER = \frac{\dot{e}_{OE}}{\dot{m}_{LNG}}$
Indirect CO <sub>2</sub> emissions	kg/kg	$INCE = \frac{\dot{m}_{Indirect\ CO_2}}{\dot{m}_{LNG}}$

### 3. Results and Discussion

(Table 5) provides detailed specifications for the various process streams involved in natural gas liquefaction using the Propane Pre-Cooled Mixed Refrigerant (C3MR) cycle. In this process, propane streams (PROP1 to PROP24) are used for the initial precooling of natural gas, followed by further cooling with mixed refrigerants (MR1 to MR2.5) to reach liquefaction temperatures. Streams NG1 to NG9 represent different stages of natural gas conditioning and cooling before

final liquefaction (LNG).

For each stream, key parameters such as vapor fraction, temperature, pressure, mass flow rate, and mole fractions of the main components (CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>8</sub>, and N<sub>2</sub>) are provided. These data are crucial for designing, simulating, and optimizing the C3MR cycle, ensuring efficient and stable operation of the liquefaction process.

**Table 5: Properties of Process Streams in Natural Gas Liquefaction via the Propane Pre-Cooled Mixed Refrigerant (C3MR) Cycle**

Stream Name	NG1	NG2	NG3	NG4	NG5	NG6	NG7	NG8	NG9	LNG	MR1	MR2
Vapour Fraction	1.0	1.0	1.0	1.0	0.8	1.0	0.0	0.0	0.1	0.0	1.0	1.0
Temperature (°C)	25.0	8.5	-5.0	-11.0	-41.0	-41.0	-100.0	-150.0	-160.4	-160.4	-27.7	35.8
Pressure (MPa)	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	0.1	0.1	0.7	1.8
Mass Flow (Ton/h)	360.0	360.0	360.0	360.0	360.0	290.1	290.1	290.1	290.1	267.0	1000.0	1000.0
Mole Frac (CH <sub>4</sub> )	0.86	0.86	0.86	0.86	0.86	0.90	0.90	0.90	0.90	0.89	0.60	0.60
Mole Frac (C <sub>2</sub> H <sub>6</sub> )	0.08	0.08	0.08	0.08	0.08	0.06	0.06	0.06	0.06	0.07	0.20	0.20
Mole Frac (C <sub>3</sub> H <sub>8</sub> )	0.06	0.06	0.06	0.06	0.06	0.04	0.04	0.04	0.04	0.04	0.10	0.10
Mole Frac (N <sub>2</sub> )	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10



The reliability of the developed simulation model for the C3MR LNG liquefaction process was evaluated through a validation study by comparing the key operating and performance parameters with the results reported by Hajji et al. (2019). As presented in (Table 6), an excellent agreement is observed between the simulation outputs and the literature data. The LNG production rate and feed gas pressure are reproduced exactly, both showing zero deviation from the reference study. Similarly, the temperature before LNG expansion and the MR to NG flow ratio are identical to those reported in the literature, confirming the correct implementation of the refrigeration cycle and mass flow distribution in the model. The predicted LNG outlet temperature of  $-160.4\text{ }^{\circ}\text{C}$  shows a very small deviation of only 0.25% from the reference value ( $-160\text{ }^{\circ}\text{C}$ ),

indicating that the cryogenic heat exchange behavior in the main heat exchanger has been accurately captured. In addition, the calculated specific power consumption ( $0.231\text{ kWh/kg}$ ) is very close to the reported value of  $0.234\text{ kWh/kg}$ , with a deviation of only 1.28%, which further demonstrates the thermodynamic consistency of the simulation. A minor difference is observed in the propane pre-cooling temperature ( $-42.2\text{ }^{\circ}\text{C}$  compared with  $-41\text{ }^{\circ}\text{C}$ ), which can be attributed to slight variations in heat exchanger modeling assumptions or numerical convergence in Aspen HYSYS. Overall, the very low deviations across the evaluated parameters confirm that the developed model accurately represents the C3MR LNG liquefaction process and can be reliably used for further process analysis and economic evaluation.

**Table 6: Validation of the C3MR LNG liquefaction process simulation results against Hajji et al. (2019)**

Parameter	Unit	Hajji et al. (2019)	This Study	Deviation (%)
LNG Production Rate	ton/h	267	267	0.00%
LNG Outlet Temperature	$^{\circ}\text{C}$	-160	-160.4	0.25%
Temperature before LNG Expansion	$^{\circ}\text{C}$	-150	-150	0.00%
Feed Gas Pressure	MPa	6.5	6.5	0.00%
Propane Refrigerant Flow	ton/h	1000	1000	0.00%
Propane Pre-cooling Temperature	$^{\circ}\text{C}$	-41	-42.2	
Specific Power Consumption (SPC)	kWh/kg	0.234	0.231	1.28%
MR to NG Flow Ratio	-	2.78	2.78	0.00%
Refrigerant Type	-	CMR	CMR	Match

As illustrated in (Figure 2), the Propane Precooling cycle shows significantly higher cooling water and overall energy consumption than the MR-Cycle. Specifically, the cooling water requirement for Propane Precooling reaches

$26.46\text{ kWh/kg}$ , which is over four times that of the MR-Cycle at  $6.10\text{ kWh/kg}$ . Similarly, overall energy consumption follows the same trend, with Propane Precooling requiring  $26.56\text{ kWh/kg}$ , compared with  $6.28\text{ kWh/kg}$  for the MR-Cycle.

In terms of electricity consumption, however, the MR-Cycle exhibits a slightly higher value (0.18 kWh/kg) than Propane Precooling (0.10 kWh/kg), primarily due to its higher compressor load and system complexity. Regarding indirect CO<sub>2</sub> emissions, the Propane Precooling cycle results in 5.34 kg CO<sub>2</sub>/kg LNG, while the MR-Cycle achieves

a lower emission level of 1.26 kg CO<sub>2</sub>/kg LNG.

These results clearly show that while the MR-Cycle results in slightly higher electricity demand, it significantly decreases water use, overall energy consumption, and CO<sub>2</sub> emissions, making it a more environmentally friendly and energy-efficient choice for LNG production.

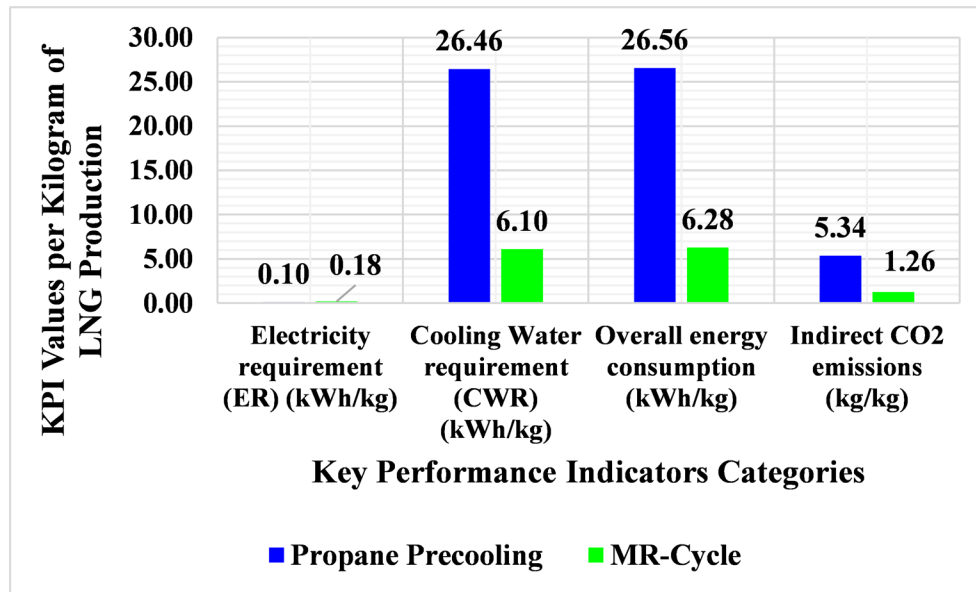


Figure 2. Comparison of Key Performance Indicators (KPIs) per Kilogram of LNG Production for Propane Precooling and MR-Cycle

According to the pie charts in (Figure 3), LNG Heat Exchangers account for the largest share of both equipment cost (43%) and installed cost (48%), underscoring their critical role in the process and the complexity of their installation. Compressors follow, showing a slight decline from 30% of equipment cost to 28% of installed cost. However, this shift masks a significant increase in absolute terms (from 37.93 to 94.83 million USD), reflecting the substantial costs associated with their installation and commissioning. Shell & Tube Heat Exchangers and Vessels contribute moderately. Vessels, in particular, show a relatively low equipment cost share (2%) that increases slightly to 3% after installation, suggesting that their installation is comparatively less complex and less capital-intensive.

(Table 7) quantitatively reinforces these

observations, showing that installed costs are typically two to three times higher than equipment purchase costs. This highlights the significant impact of installation activities such as construction, integration, and commissioning on total capital expenditure and emphasizes the importance of careful planning during the engineering and implementation phases.

Table 7: Comparison of Purchase and Installation Costs for Major Equipment in the LNG Unit

Equipment Type	Equipment Cost	Installed Cost
Compressors Cost	37.93	94.83
Heat Exchangers (LNG) Cost	46.18	161.63
Heat Exchangers (Shell&Tube) Cost	20.01	70.03
Vessels Cost	2.36	9.42

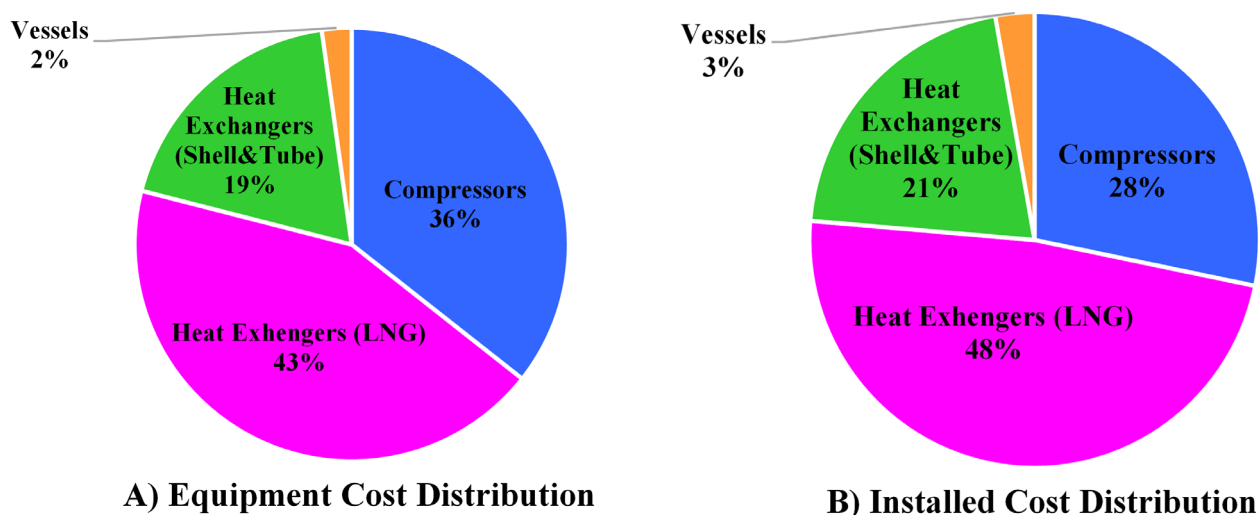


Figure 3. Equipment and Installed Cost Breakdown for Main Units in LNG Facility

(Table 7) provides a detailed breakdown of the Capital Expenditure (CAPEX) for the LNG facility, offering a clear view of the investment structure required for project implementation. The Total Equipment Cost is reported at 106.47 million USD, while the Total Installed Cost rises to 335.91 million USD, reflecting the significant role of installation, construction, and integration efforts. A 25% contingency allowance, equal to 83.98 million USD, is included to address uncertainties and potential cost overruns. The Battery Limit Investment, which encompasses all direct costs within the facility boundary, amounts to 526.37 million USD. Furthermore, Offsite Costs and General Services, which cover infrastructure such as utility systems, access roads, and project administration, contribute an additional 105.27 million USD.

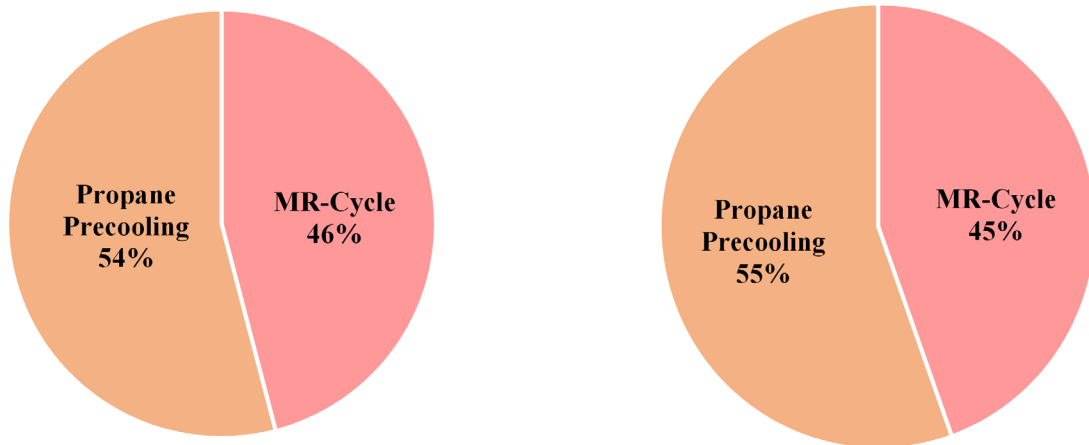
These costs collectively form the Total Fixed Capital (TFC) of 631.64 million USD. In addition, a Total Working Capital (TWC) of 157.91 million USD is allocated to support initial operational needs, such as raw material procurement and early-stage process stabilization. Altogether, the Total Capital Cost for the LNG project is estimated at 789.55 million USD, as detailed in (Table 8). This comprehensive CAPEX assessment

is critical for financial planning, risk mitigation, and investment decision-making in large-scale energy infrastructure projects.

Table 8: Capital Expenditure (CAPEX) Breakdown for the LNG Facility

CAPEX Parameters	Value
Total Equipment Cost (MUSD)	106.47
Total Installed Cost (MUSD)	335.91
Contingency, 25% (MUSD)	83.98
Battery Limit Investment (MUSD)	526.37
Offsite Cost + General Services (MUSD)	105.27
Total Fix Capital Cost (TFC) (MUSD)	631.64
Total Working Capital (TWC) (MUSD)	157.91
Total Capital Cost (MUSD)	789.55

As shown in (Figure 4), the Propane Precooling unit accounts for a larger share of both equipment costs (54%) and CAPEX (55%) than the MR-Cycle unit. This suggests that precooling equipment is more capital-intensive, likely due to its scale or technical requirements.



A) Unit-Wise Equipment Cost Distribution

B) Unit-Wise CAPEX Distribution

Figure 4. Unit-wise Distribution of Equipment Cost and CAPEX

As shown in (Table 9), natural gas accounts for the largest share of feedstock and utility expenses for producing one ton of LNG, followed by power and cooling water. The table provides a detailed breakdown of these costs, indicating that natural gas accounts for 200.85 USD/Ton, while power and cooling water costs are 27.84 and 24.42 USD/Ton, respectively. This emphasizes the dominant role of natural gas pricing in determining the overall production cost structure.

**Table 9: Feedstock and Utility Costs per Ton of LNG Production**

Cost Item	Value
NG Cost (USD/Ton)	200.85
Power Cost (USD/Ton)	27.84
Cooling Water Cost (USD/Ton)	24.42

A detailed economic analysis of the LNG production process is presented in (Table 10). The total variable cost is estimated at 253.12 USD/Ton, comprising the direct expenses for feedstock and utilities as outlined previously in (Table 8). Labor costs are categorized into

operating labor, maintenance labor, and control laboratory labor, totaling 7.86 USD/Ton. Additional direct expenses, including maintenance materials and operating supplies, bring the total direct cost to 267.29 USD/Ton.

Indirect costs consist of plant overhead (4.72 USD/Ton), taxes and insurance (5.97 USD/Ton), and depreciation (29.87 USD/Ton), totaling 307.85 USD/Ton at the plant gate. Corporate-level expenses such as general and administrative, sales, and research costs (20.01 USD/Ton) and a return on investment (ROI) of 44.81 USD/Ton at 15% per year of total fixed capital (TFC) are added to determine the final product value, which is calculated at 372.67 USD/Ton. This analysis reveals that variable costs, particularly feedstock and utility expenses, dominate the overall cost structure of LNG production. Moreover, the significant depreciation and ROI shares highlight the capital-intensive nature of liquefaction facilities. The sensitivity of total production costs to natural gas price fluctuations underscores the need for careful pricing strategies and long-term supply agreements to ensure plant profitability.

**Table 10: Detailed Cost Structure and Economic Evaluation for LNG Production**

CAPEX Parameters	Value
Cost Item	Value (USD/Ton.)
Variable Cost	253.12
Operating Labor, 2/Shift \$55/hr	3.37
Maintenance Labor, 1.6% YR of BLI	3.98
Control Lab labor, 15% of oper labor	0.51
Labor Cost	7.86
Maintenance Materials, 2.4% YR of BLI	5.97
Operating Supplies, 10% of operating labor	0.34
Total Direct Cost	267.29
Plant Overhead, 60% of Labor Cost	4.72
Taxes and insurance, 2% Yr of TFC	5.97
Plant Cash Costs	277.98
Depreciation, 10% YR of TFC	29.87
Plant Gate Costs	307.85
G&A Sales Research	20.01
ROI before taxes, 15% Yr of TFC	44.81
Product Value	372.67

As shown in (Table 11), the LNG production plant demonstrates strong profitability indicators. With a market LNG price of 600 USD/Ton and a calculated product value (plant gate cost) of 372.67 USD/Ton (from Table 10), the resulting net profit is estimated at 227.33 USD/Ton. This translates into an annual net profit of approximately 524.39 MUSD, based on the designed plant capacity.

The financial viability is further supported by a favorable payback period (PBP) of only 1.51 years, indicating a rapid recovery of the initial capital investment. Additionally, the calculated rate of return (ROR) is 66.42%, substantially

exceeding typical industry benchmarks for large-scale energy infrastructure projects. These results highlight the economic attractiveness of the proposed LNG facility, driven primarily by the competitive margin between production costs and prevailing LNG market prices. Moreover, the sensitivity of the financial outcomes to LNG market price fluctuations and natural gas feedstock costs suggests that maintaining long-term price stability through strategic supply contracts and hedging mechanisms would be essential to securing the sustained profitability of the operation.

**Table 11: Key Economic Indicators for LNG Plant Operation**

Cost/Indicator	Value	Unit
LNG Cost (Market)	600	USD/Ton
Net Profit	227.33	USD/Ton
Net Profit	524.40	MUSD/Year
PBP (Year)	1.50	Year
ROR	66.42	%

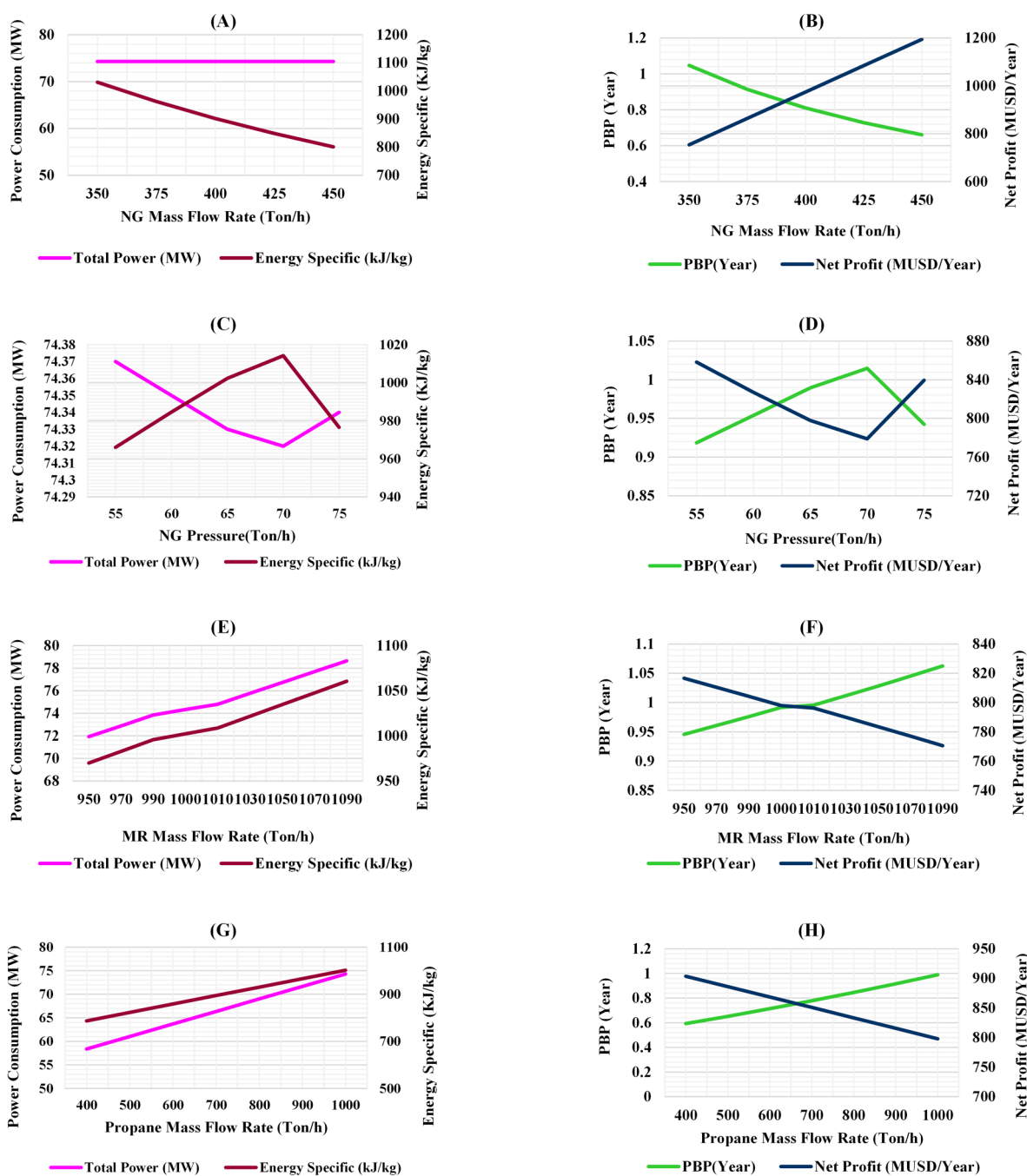
(Figure 5) shows how key technical and economic performance indicators are affected by changes in four main operating parameters of the C3MR-based LNG liquefaction process: NG mass flow rate, NG pressure, MR flow rate, and propane flow rate.

As shown in (Figure 5A-B), increasing the natural gas (NG) feed rate from 350 to 450 ton/h significantly reduces the specific energy consumption from 1031 to 801.1 kJ/kg, while total power consumption remains nearly constant at 74.3 MW. This improved energy efficiency translates directly into enhanced economic outcomes, with the payback period (PBP) decreasing from 1.05 to 0.66 years and the annual net profit increasing from 753.9 to 1194.6 MUSD. This trend is attributed to scale effects, in which higher LNG production rates lead to better utilization of fixed energy and capital costs.

(Figure 5C-D) demonstrates the influence of NG pressure on system performance. While total power remains relatively stable, specific energy shows a nonlinear trend, reaching a minimum at 55 bar and a peak at 70 bar. From an economic perspective, 65 bar yields the most favorable trade-off between cost and performance, with a PBP of approximately 0.99 years and a net profit of 797.8 MUSD/year. Increasing pressure beyond this point imposes higher compression energy without a proportional increase in LNG output, ultimately diminishing economic

returns. The impact of the mixed refrigerant (MR) flow rate is depicted in (Figure 5E-F) as the MR flow increases from 950 to 1090 ton/h, both power consumption and specific energy rise from approximately 71.9 to 78.7 MW and from 970 to 1060 kJ/kg, respectively. This results in a gradual deterioration of economic indicators: the PBP increases while net profit declines. The trend suggests diminishing returns from overcirculation of MR, which increases compressor load without significant thermal benefit.

Finally, (Figure 5G-H) evaluates the effect of propane flow rate. Increasing propane from 400 to 1000 ton/h leads to a near-linear increase in both power consumption (from 58.4 to 74.3 MW) and specific energy (from 787 to 1002 kJ/kg). Although additional propane enhances precooling, it also increases compression duty, adversely affecting overall economic feasibility. The highest profitability is achieved at lower propane flow rates, beyond which the PBP increases sharply and net profit declines. In summary, the sensitivity analysis underscores that the optimal operation of the C3MR liquefaction process requires a higher NG throughput, moderate MR and propane flow rates, and an NG pressure near 65 bar. These conditions, taken together, ensure a favorable balance between energy efficiency and economic viability.



**Figure 5. Sensitivity of Technical (Power and Specific energy) and Economic (PBP and Profit) Indicators of the C3MR LNG Process to Variations in: (A-B) NG mass Flow Rate, (C-D) NG Pressure, (E-F) MR Flow Rate, and (G-H) Propane Flow Rate**

## 4. Conclusion and Recommendations for Future Works

This study aimed to provide a comprehensive techno-economic evaluation and process sensitivity analysis of a C3MR-based LNG liquefaction system to support operational optimization and investment decisions.

The results show that the proposed C3MR configuration is both technically reliable and economically viable across a wide range of operating conditions.

From a technical standpoint, the mixed refrigerant (MR) cycle proved to have superior overall energy efficiency and a lower environmental impact. Specifically, the MR

cycle greatly reduced cooling water demands and indirect CO<sub>2</sub> emissions compared to the propane precooling section, while maintaining similar electricity consumption. The specific energy consumption (SEC) values obtained are within the lower range reported for industrial C3MR systems, confirming the effectiveness of the proposed process configuration.

From an economic perspective, the LNG plant demonstrates solid profitability. At a market price of 600 USD/Ton, the calculated plant gate cost of 372.67 USD/Ton yields a net profit of 227.33 USD/Ton, leading to an annual net profit of roughly 524.4 MUSD. The payback period (PBP) of 1.5 years and a return on investment (ROI) of 66.42% suggest quick capital recovery and strong financial competitiveness compared to other liquefaction cycles reported in the literature. These metrics emphasize the strong link between energy efficiency improvements and better economic performance.

The sensitivity analysis further clarified the link between operating variables and process performance. Increasing natural gas throughput improved energy efficiency and lowered unit capital costs, while excessive circulation of mixed refrigerant or propane raised compression loads and negatively impacted both SEC and economic performance. An optimal operating range was identified at a natural gas pressure of about 65 bar, moderate refrigerant flow rates, and high feed throughput, providing the best balance between efficiency and profitability.

In summary, the integrated techno-economic and sensitivity analysis confirms that the C3MR cycle is a reliable, scalable, and economically viable solution for large-scale LNG production. The results directly support informed process design, operational optimization, and strategic investment decisions in LNG infrastructure development.

To further improve the performance, robustness, and sustainability of LNG production systems, future research should focus on several

key areas. These include integrating renewable energy sources, such as solar power and waste heat recovery, to decrease external energy demand; conducting dynamic simulation and operability analysis under variable feed and load conditions; applying exergy-based optimization to systematically reduce energy losses throughout the process; performing comprehensive techno-environmental assessments that incorporate carbon pricing mechanisms; and validating advanced mixed refrigerant compositions and innovative cryogenic heat exchanger configurations through experiments or pilot-scale studies.

## Nomenclature

<i>ASPEN</i>	Advanced System for Process Engineering
<i>BLI</i>	Battery Limits Investment
<i>C3MR</i>	Propane Pre-Cooled Mixed Refrigerant
<i>CAPEX</i>	Capital Expenditure
<i>CEPCI</i>	Chemical Engineering Plant Cost Index
<i>HHV</i>	Higher Heating Value
<i>KPIs</i>	Key performance indicators
<i>LNG</i>	Liquefied Natural Gas
<i>MR</i>	Mixed Refrigerant
<i>MUSD</i>	Million United States dollar
<i>NG</i>	Natural Gas
<i>OPEX</i>	Operating expenditure
<i>PBP</i>	Payback Period
<i>PFD</i>	Process Flow Diagram
<i>PR</i>	Peng–Robinson
<i>PR-EOS</i>	Peng–Robinson equation of state
<i>ROR</i>	Rate of Return
<i>SEC</i>	specific energy consumption

<i>TCC</i>	Total Capital Cost
<i>TCI</i>	Total Capital Investment
<i>TEC</i>	Total Equipment Cost
<i>TFC</i>	Total Fixed Capital
<i>TIC</i>	Total Installed Cost
<i>TWC</i>	Total Working Capital
<i>USD</i>	United States dollar

## References

- Ahmed, R., Mahadzir, S., Ferdush, J., Matovu, F., Mota-Babiloni, A., Hafyan, R. H., 2024. Surrogate-assisted constrained hybrid particle swarm optimization algorithm for propane pre-cooled mixed refrigerant LNG process optimization. *Energy* 305, 132165. <https://doi.org/10.1016/j.energy.2024.132165>
- Alabdulkarem, A., Mortazavi, A., Hwang, Y., Radermacher, R., Rogers, P., 2011. Optimization of propane pre-cooled mixed refrigerant LNG plant. *Applied Thermal Engineering* 31(6-7), 1091-1098. <https://doi.org/10.1016/j.applthermaleng.2010.12.003>
- Almeida-Trasvina, F., Smith, R., 2023. Design and optimisation of novel cascade mixed refrigerant cycles for LNG production- Part I: Benchmark cascade cycles. *Chemical Engineering Research and Design* 190, 619-633. <https://doi.org/10.1016/j.cherd.2022.12.046>
- Balcombe, P., Staffell, I., Kerdan, I. G., Speirs, J. F., Brandon, N. P., Hawkes, A. D., 2021. How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis. *Energy* 227, 120462. <https://doi.org/10.1016/j.energy.2021.120462>
- Bansod, Y., Jafari, M., Pawanipagar, P., Ghasemzadeh, K., Spallina, V., D'Agostino, C., 2025. Techno-economic assessment of bio-based routes for acrylic acid production. *Green Chemistry* 27(35), 10612-10632. <https://doi.org/10.1039/D5GC01769F>
- Behroozsarand, A., Ghasemzadeh, K., 2022. GTL Process Simulation and Sensitivity Analysis: Zero CO<sub>2</sub> Emission and Productivity Improvement. *Chemical Process Design* 1(1), 1-16. <https://doi.org/10.22111/cpd.2022.42322.1000>
- Cui, F., Pan, L., Pang, Y., Chen, J., Shi, F., Liang, Y., 2024. A new multi-objective optimization strategy for improved C3MR liquefaction process. *Processes* 12(3), 542. <https://doi.org/10.3390/pr12030542>
- Falsafi, M., Vatani, A., Abbasi, M., Palizdar, A., 2024. An efficient thermo-hydraulic model for the investigation of a plate-fin heat exchanger in a single mixed refrigerant process. *International Journal of Heat and Mass Transfer* 227, 125507. <https://doi.org/10.1016/j.ijheatmasstransfer.2024.125507>
- Fikri, M., Hendrarsakti, J., Sambodho, K., Felayati, F., Octaviani, N., Giranza, M., Hutomo, G., 2018. Estimating capital cost of small scale LNG carrier. In: *Proceedings of the 3rd International Conference on Marine Technology (SENTA)*, Surabaya, Indonesia, pp. 225-229. <https://doi.org/10.5220/0008542102250229>
- Ghasemzadeh, K., Jafari, M., Sari, A., Babalou, A. A., 2016. Performance investigation of membrane process in natural gas sweetening by membrane process: modeling study. *Chemical Product and Process Modeling* 11(1), 23-27. <https://doi.org/10.1515/cppm-2015-0054>
- Ghasemzadeh, K., Jafari, M., Basile, A., 2017. Theoretical study of various configurations of membrane processes for olefins separation. *International Journal of Membrane Science and Technology* 4(1), 1-7. <https://doi.org/10.15379/2410-1869.2017.04.01.01>
- Ghasemzadeh, K., Jafari, M., Bansod, Y., Spallina, V., Ferrari, M.-C., Iulianelli, A., 2025. Integrated environmental and techno-economic assessment for membrane-based gas-to-liquid process to green flare gas valorisation. *Fuel Processing Technology* 279, 108357. <https://doi.org/10.1016/j.fuel.2025.108357>

doi.org/10.1016/j.fuproc.2025.108357

Hajji, A., Chahartaghi, M., Kahani, M., 2019. Thermodynamic analysis of natural gas liquefaction process with propane pre-cooled mixed refrigerant process (C3MR). *Cryogenics* 103, 102978. <https://doi.org/10.1016/j.cryogenics.2019.102978>

Jafari, M., Ghasemzadeh, K., Yousefi, A. T., Basile, A., 2019. Comparative study of membrane and absorption processes performance and their economic evaluation for CO<sub>2</sub> capturing from flue gas. *Gas Processing Journal*. <https://doi.org/10.22108/gpj.2019.116263.1053>

Jafari, M., Deljoo, M. S., Vatani, A., 2020a. Simulation and economic evaluation of polygeneration system for coproduction of power, steam, CH<sub>3</sub>OH, H<sub>2</sub>, and CO<sub>2</sub> from flare gas. *Iranian Journal of Oil and Gas Science and Technology* 9(4), 93-114. <https://doi.org/10.22050/ijogst.2020.227023.1547>

Jafari, M., Sarrafzadeh, M.-H., Ghasemzadeh, K., 2020b. Simulation and economic evaluation of heat and power generation from flare gases in a combined cycle power plant. *Energy Equipment and Systems* 8(4), 307-322. <https://doi.org/10.22059/ees.2020.241289>

Jafari, M., Khalili-Garakani, A., 2021a. Simulation and techno-economic analysis of hydrotreating process of mazut. *Applied Research in Chemical - Polymer Engineering* 5(1), 17-30. <https://doi.org/10.22111/jarce.2021.194>

Jafari, M., Khalili-Garakani, A., 2021b. Techno-economic analysis of heavy fuel oil hydrodesulfurization process for application in power plants. *Iranian Journal of Oil and Gas Science and Technology* 10(1), 40-65. <https://doi.org/10.22050/ijogst.2020.254534.1569>

Jafari, M., Nezhadfar, M., Khalili-Garakani, A., 2021c. Simulation and economic analysis of combined desalinated water and power generation from associated gases of Cheshmeh Khosh. *Iranian Journal of Oil and Gas Science and Technology* 10(1), 1-14. <https://doi.org/10.22050/ijogst.2020.219350.1536>

org/10.22050/ijogst.2020.219350.1536

Jafari, M., Vatani, A., Deljoo, M. S., Khalili-Garakani, A., 2021d. Techno-economic analysis of flare gas to gasoline (FGTG) process through dimethyl ether production. *Journal of Gas Technology* 6(2), 28-44. [http://jgt.irangi.org/article\\_251676.html](http://jgt.irangi.org/article_251676.html)

Jafari, M., Khorshidian, M., Rahimi Esboee, M., Kord Firouzjaei, V., Vatani, A., 2023. Design and simulation of hydrogen production from diesel reforming for fuel cell applications. *Journal of Gas Technology* 8(2), 56-73. [https://jgt.irangi.org/article\\_714881.html](https://jgt.irangi.org/article_714881.html)

Jafari, M., Spallina, V., Ghasemzadeh, K., 2024a. Techno-economic assessment of flare gas valorisation during membrane-based GTL process by net-zero strategy. *Energy Conversion and Management* 315, 118796. <https://doi.org/10.1016/j.enconman.2024.118796>

Jafari, M., Vatani, A., Mohammadi, T., 2024b. CFD modeling of braid-reinforced hollow fiber membranes for efficient water and bovine serum albumin (BSA) separation. *Journal of Water Process Engineering* 65, 105746. <https://doi.org/10.1016/j.jwpe.2024.105746>

Khan, S. R., Zeeshan, M., Fatima, S., Ciolkosz, D., Dimitriou, I., Jin, H., 2023. A comparative techno-economic analysis of combined oil and power production from pyrolysis and co-pyrolysis plants utilizing rice straw and scrap rubber tires. *Fuel* 348, 128639. <https://doi.org/10.1016/j.fuel.2023.128639>

Khosravi, M., Jafari, M., Ghasemzadeh, K., Lulianelli, A., 2025. Enhancing styrene production: CFD analysis of a Pd-based membrane reactor to carry out ethylbenzene dehydrogenation. *Fuel Processing Technology* 270, 108191. <https://doi.org/10.1016/j.fuproc.2025.108191>

Palizdar, A., Ramezani, T., Nargessi, Z., AmirAfshar, S., Abbasi, M., Vatani, A., 2019. Advanced exergoeconomic evaluation of a mini-scale nitrogen dual expander process for liquefaction of natural gas. *Energy* 168, 542-557.

- <https://doi.org/10.1016/j.energy.2018.11.058>
- Primabudji, E., Morosuk, T., Tsatsaronis, G., 2019. Multi-objective optimization of propane pre-cooled mixed refrigerant (C3MR) LNG process. *Energy* 185, 492-504. <https://doi.org/10.1016/j.energy.2019.07.035>
- Sanavandi, H., Ziabasharhagh, M., 2016. Design and comprehensive optimization of C3MR liquefaction natural gas cycle by considering operational constraints. *Journal of Natural Gas Science and Engineering* 29, 176-187. <https://doi.org/10.1016/j.jngse.2015.12.055>
- Shady, R., Ahmed, S. F., Sleiti, A. K., 2024. Operation optimization of propane pre-cooled mixed refrigerant LNG process: A novel integration of knowledge-based and constrained Bayesian optimization approaches. *Chemical Engineering Science* 300, 120560. <https://doi.org/10.1016/j.ces.2024.120560>
- Shahab-Deljoo, M., Medi, B., Kazi, M.-K., Jafari, M., 2023. A techno-economic review of gas flaring in Iran and its human and environmental impacts. *Process Safety and Environmental Protection* 173, 642-665. <https://doi.org/10.1016/j.psep.2023.03.051>
- Sleiti, A. K., Al-Ammari, W. A., 2023. Novel integration between propane pre-cooled mixed refrigerant LNG process and concentrated solar power system based on supercritical CO<sub>2</sub> power cycle. *Energy Reports* 9, 4872-4892. <https://doi.org/10.1016/j.egy.2023.04.012>
- Stewart, W. R., Shirvan, K., 2022. Capital cost estimation for advanced nuclear power plants. *Renewable and Sustainable Energy Reviews* 155, 111880. <https://doi.org/10.1016/j.rser.2021.111880>
- Towler, G., Sinnott, R., 2021. *Chemical engineering design: Principles, practice and economics of plant and process design*, 2nd ed. Butterworth-Heinemann, Oxford.
- Vatani, A., Mehrpooya, M., Palizdar, A., 2014. Advanced exergetic analysis of five natural gas liquefaction processes. *Energy Conversion and Management* 78, 720-737. <https://doi.org/10.1016/j.enconman.2013.11.050>
- Wang, J., Deng, M., Chen, T., 2025. How does the penetration of new energy vehicles affect global energy security? Empirical evidence from multiple countries. *Energy Strategy Reviews* 62, 101945. <https://doi.org/10.1016/j.esr.2025.101945>
- Yoon, S., Mun, H., Ga, S., Park, J., Lee, I., Chung, Y. G., 2025. Modeling, screening, and techno-economic evaluation of metal-organic frameworks for boil-off gas capture during intercontinental transportation of LNG. *Chemical Engineering Journal* 507, 160517. <https://doi.org/10.1016/j.cej.2025.160517>
- Yu, Y., Su, J., Wu, B., 2026. A sophisticated computational approach for flexural strength prediction and mix proportion optimization of steel fiber-reinforced concrete. *Applied Soft Computing* 186, 114181. <https://doi.org/10.1016/j.asoc.2025.114181>
- Yuan, J., Shi, X., He, J., 2024. LNG market liberalization and LNG transportation: Evaluation based on fleet size and composition model. *Applied Energy* 358, 122657. <https://doi.org/10.1016/j.apenergy.2024.122657>
- Zhai, C., Cao, Z., Wang, Y., Abdou-Tankari, M., Yu, J., Lei, Z., 2025. A reverse incentive-based demand response strategy for shared energy storage in industrial microgrids: Optimization, scheduling, and investment analysis. *Energy* 330, 136882. <https://doi.org/10.1016/j.energy.2025.136882>
- Zhao, Y., Qian, C., Shi, G., Li, M., Qiu, Z., Zhang, B., Wu, Z., 2024. Study on rapid simulation of the pre-cooling process of a large LNG storage tank with the consideration of digital twin requirements. *Energies* 17(14), 3471. <https://doi.org/10.3390/en17143471>

## تحلیل فنی-اقتصادی و تحلیل حساسیت فرآیند مایع سازی گاز طبیعی با استفاده از چرخه مبرد مخلوط پیش سرد شده با پروپان

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### چکیده

گاز طبیعی مایع شده نقش اساسی در گذار جهانی انرژی ایفا می کند، زیرا امکان انتقال گاز طبیعی در مسافت های طولانی را با میزان انتشار آلاینده کمتر فراهم می سازد. از این رو، بهبود بازده انرژی و امکان پذیری اقتصادی فرآیندهای مایع سازی گاز طبیعی اهمیت ویژه ای دارد. در این پژوهش، یک تحلیل جامع فنی-اقتصادی به همراه ارزیابی حساسیت فرآیند مایع سازی گاز طبیعی با استفاده از چرخه مبرد مخلوط پیش سرد شده با پروپان ارائه شده است. یک شبیه سازی حالت پایا در نرم افزار اسپن هایسیس نسخه ۲۱ توسعه داده شد و برای مدل سازی دقیق رفتار برودتی جریان های چند جزئی از معادله حالت پنگ-رابینسون استفاده گردید. فرآیند به دو زیر سامانه یکپارچه شامل پیش سرد سازی با پروپان و زیر سرد سازی با مبرد مخلوط تقسیم شد و عملکرد آن با استفاده از شاخص های کلیدی نظیر مصرف انرژی، نیاز توان الکتریکی و انتشار غیر مستقیم دی اکسید کربن ارزیابی گردید.

نتایج نشان می دهد که اگرچه چرخه مبرد مخلوط به توان الکتریکی اندکی بیشتر نسبت به مرحله پیش سرد سازی با پروپان نیاز دارد، اما منجر به کاهش مصرف کل انرژی، کاهش نیاز به آب خنک کننده و کاهش قابل توجه انتشار آلاینده های زیست محیطی می شود. از منظر اقتصادی، برآورد هزینه ها بر اساس شاخص های به روز هزینه تجهیزات فرایندی بیانگر آن است که این بهبودهای فنی به عملکرد مالی مطلوبی منجر شده و با سودآوری بالا و دوره بازگشت سرمایه کوتاه در شرایط متعارف بازار گاز طبیعی مایع شده همراه است. تحلیل حساسیت همچنین نشان می دهد که نرخ های بالاتر خوراک گاز طبیعی، دبی های متوسط مبرد و فشار ورودی نزدیک به ۵۶ بار، بهترین توازن میان بازده انرژی و بازده اقتصادی را فراهم می کنند. در مجموع، یافته های این پژوهش تأیید می کند که چرخه مبرد مخلوط پیش سرد شده با پروپان گزینه ای کارآمد و عملی برای تولید گاز طبیعی مایع شده در مقیاس بزرگ است و به طور مؤثری بهبود عملکرد ترمودینامیکی را با نتایج اقتصادی مطلوب پیوند می دهد.

**واژگان کلیدی:** چرخه مبرد مخلوط پیش سرد شده با پروپان، گاز طبیعی مایع شده، ارزیابی فنی-اقتصادی، شبیه سازی فرایندی، بهینه سازی فرایند، تحلیل حساسیت