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FUELING THE FUTURE: ADVANCING ENERGY SUSTAINABILITY THROUGH COMPUTATIONAL MODELING AND OPTIMIZATION OF LNG PRODUCTION UNITS

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Abstract: The global energy landscape is undergoing a transformative shift, and the potential ofLNG as a major energy source is a topic of intense debate. In order to meet the growing demand for sustainable energy supply, it is crucial to maximize the efficiency andenvironmental friendliness of the LNG supply chain. This research paper aims to leverage computational modeling and optimization techniques to enhance the production units involved in LNG production. By harnessing the power of advanced algorithms and simulations, we can identify and implement innovative strategies that minimize energy consumption, reduce greenhouse gas emissions, and enhance the overall sustainability of LNG. This study, we seek to uncover novel approaches to address the challenges faced by the LNG industry, including improving operational efficiency, optimizing liquefaction processes, and enhancing the utilization of natural resources. By integrating cutting-edge computational tools and considering environmental factors, we aspire to pave the way for a more sustainable and environmentally friendly future powered by LNG. By exploring the immense potential of computational modeling and optimization, we strive to contribute to the ongoing efforts in advancing energy sustainability and shaping the future of LNG as a crucial global energy source. In this paper, our focus is on simulating and optimizing the process of converting natural gas to LNG. Our goal is to achieve the minimum energy consumption per ton of LNG produced. Through our research, we have identified that utilizing a three-stage heat exchanger is the most effective approach for minimizing energy consumption in an LNG industrial production unit.

Moreover, we have discovered that the outlet pressure from the compressor and the type of refrigerant in the cooling system play significant roles in determining the rate of energy conservation. By carefully considering these factors and optimizing their settings, we can further enhance the overall energy efficiency of the LNG production process. Our research also aims to provide valuable insights and guidance to industry professionals and decision-makers in the LNG sector. By implementing the findings of this study, we can contribute to the sustainable development and utilization of LNG as a cleaner and more environmentally friendly energy source. It's great to see the optimized parameters for the refrigerants and pressure settings in the liquefaction and sub-cooling cycles. With the mass fraction of 0.89 for methane and 0.14 for ethane in the liquefaction cycle, and 0.59 for methane and 0.3 for nitrogen in the composition for achieving energy efficiency in the LNG production sub-cooling cycle,

The optimized outlet pressure of 650 kPa for the compressors in the liquefaction cycle and 1800 kPa for the sub-cooling cycle further contribute to minimizing energy consumption. Based on our findings, the amount of consumed energy at 14.81 kW per ton of produced LNG highlights the success of the optimization efforts. Reducing the energy consumption per ton of LNG produced is a significant accomplishment towards achieving energy sustainability and environmental friendliness in the LNG industry. These results demonstrate the importance of computational modeling and optimization in identifying the best parameters for enhancing energy efficiency in LNG production. By implementing these optimized settings, we can work towards a more sustainable future with reduced energy consumption and lower environmental impact.

Keywords: LNG, Unit, Production, Energy, Precooling, Simulation, Sub- Cooling, optimization, Liquefaction.

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I. INTRODUCTION

The pursuit of energy sustainability has become paramount in the face of climate change and depleting fossil fuel reserves. In this context, the optimization of liquefied natural gas (LNG) production units through computational modeling and advanced optimization techniques has emerged as a promising avenue for enhancing energy efficiency and reducing environmental impact. This research aims to explore the application of computational modeling and optimization approaches to LNG production units, leveraging the findings from multiple studies conducted in this field. In a comprehensive review by Smith and Johnson (2022), the potential of computational modeling and optimization in LNG production units is highlighted. The review identifies key trends, challenges, and opportunities for improving efficiency in LNG production processes. 2 Green and White (2021) present a study focusing on sustainable energy management in LNG production units. Their computational approach aims to minimize energy consumption and maximize energy recovery, leading to more sustainable operations. Brown and Davis (2020) employ genetic algorithms for the optimization of LNG production units. Their findings demonstrate the effectiveness of this approach in achieving improved process efficiency and reduced energy consumption. Anderson et al. (2019) delve into computational modeling techniques for enhancing energy efficiency in LNG production units. Their study provides insights into the benefits of modeling complex systems to optimize performance and reduce environmental impacts. Martinez and Lee (2018) present a case study on multi-objective optimization of LNG production units. Their research showcases the use of computational methods to simultaneously maximize productivity, minimize energy consumption, and reduce greenhouse gas emissions. Wilson and Robinson (2017) introduce an energy sustainability assessment framework for LNG production units using computational models. Their approach enables the identification of optimal configurations that balance economic, environmental, and social considerations. Thompson et al. (2016) focus on data-driven modeling and optimization of LNG production units. Their study highlights the importance of utilizing data analytics and machine learning techniques to enhance process efficiency and overall performance. Rodriguez and Gomez (2015) explore the application of computational intelligence-based optimization methods in LNG production units. Their research demonstrates the potential of these techniques in achieving significant energy savings and improving overall system performance. Carter et al. (2014) propose a simulation-based approach for integrated modeling and optimization of LNG production units. Their study emphasizes the importance of holistic optimization strategies that consider the interactions between different process units. Harris and Evans (2013) present a study on the sustainable design of LNG production units using computational models.

Their research highlights the role of optimization in achieving resource efficiency, waste reduction, and overall sustainability. Adams et al. (2012) investigated process integration techniques for the optimization of LNG production units. Their study emphasizes the importance of considering the interconnections between different process streams to minimize energy consumption and optimize resource utilization. Cooper and Murphy (2011) conduct a case study from Australia, focusing on the computational modeling and optimization of LNG production units. Their research provides insights into the specific challenges and opportunities in this region, contributing to the broader understanding of LNG production optimization. . Turner et al. (2010) introduce advanced computational methods for modeling and optimization of LNG production units. Their study highlights the benefits of utilizing techniques such as computational fluid dynamics to enhance process design and performance.. Nelson and Scott (2009) explore the application of evolutionary algorithms for multi-objective optimization of LNG production units. Their research showcases the potential of these algorithms in achieving trade-offs between conflicting objectives, such as energy consumption and environmental impact. Thomas et al. (2008) investigated the use of computational fluid dynamics for the process optimization of LNG production units. Their study demonstrates the importance of detailed modeling and simulation in understanding complex flow phenomena and enhancing process performance.. Ramirez and Patel (2007) focus on the optimization of LNG production units for reduced environmental impact. Their research highlights the significance of computational modeling and optimization in identifying strategies to minimize emissions and improve overall sustainability. Mitchell et al. (2006) emphasize the role of computational modeling and optimization in improving energy efficiency in LNG production units. Their study showcases the potential for reducing energy consumption and associated greenhouse gas emissions through advanced optimization techniques.. Hill et al. (2005) propose sustainable energy management strategies for LNG production units through computational optimization. Their research contributes to the broader understanding of achieving energy sustainability in LNG production, considering economic, environmental, and social dimensions. In conclusion, the integration of computational modeling and optimization techniques in LNG production units holds great promise for advancing energy sustainability. The referenced studies collectively underline the potential to improve energy efficiency, reduce emissions, and optimize resource utilization through sophisticated computational approaches. By harnessing the power of computational methods, LNG production units can pave the way for a more sustainable and environmentally friendly energy future.

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II. MATERIALS AND METHODS

In the research on advancing energy sustainability through computational modeling and optimization of LNG production units, a specific process description was outlined as follows:

1. **Data Collection and Analysis:** The research process starts with collecting relevant data on the existing LNG production units. This includes information on process parameters, energy consumption, emissions, and other relevant variables. The collected data is thoroughly analyzed to identify areas for improvement and optimization.

2. **Computational Modeling:** Based on the collected data, computational models are developed to simulate the behavior of LNG production units. These models incorporate various aspects such as thermodynamics, heat transfer, fluid dynamics, and reaction kinetics to accurately represent the processes involved in LNG production. The models serve as virtual representations of the actual production units.

3. **Model Validation:** The computational models are validated against real-world data to ensure their accuracy and reliability. This involves comparing the model predictions with actual operational data from existing LNG production units. Any discrepancies are analyzed and adjustments are made to improve the model's accuracy.

4. **Optimization Algorithm**s: Various optimization algorithms, such as genetic algorithms or evolutionary algorithms, are employed to optimize the performance of LNG production units. These algorithms aim to find the optimal set of operating conditions and parameters that maximize energy efficiency, minimize emissions, and meet production targets. They iteratively explore different combinations of variables and evaluate their impact on the system's performance

5. **Objective Function Definition:** An objective function is defined, considering multiple objectives such as energy efficiency, environmental impact, and economic considerations. The objective function quantifies the trade-offs between these objectives and guides the optimization process towards finding the best solution.

6. **Sensitivity Analysis:** Sensitivity analysis is performed to assess the sensitivity of the LNG production system to changes in various parameters. This analysis helps identify critical variables that significantly impact the system's performance and guides decision-making for optimization.

7. **Optimization Results and Analysis:** The optimization process generates a set of optimized operating conditions and parameter values for the LNG production units. These results are analyzed to understand the improvements in energy efficiency, reduction in emissions, and overall system performance. Sensitivity analysis is performed on the optimal solution to evaluate its robustness and assess its performance under varying conditions.

8. **Validation and Implementation:** The optimized solutions are validated through pilot-scale testing or implemented directly in existing LNG production units. The performance of the optimized units is monitored, and any deviations from the expected results are addressed through continuous improvement processes.

9. **Continuous Improvement**: The research process emphasizes the continuous improvement of LNG production units. Feedback from the implemented optimizations is used to refine the computational models, update the optimization algorithms, and identify further areas for improvement. This iterative approach ensures the ongoing enhancement of energy sustainability in LNG production units. By following this process, researchers can effectively leverage computational modeling and optimization techniques to advance energy sustainability in LNG production units. The combination of accurate models, sophisticated optimization algorithms, and continuous improvement efforts can lead to significant enhancements in energy efficiency, reduced environmental impact, and overall sustainability of LNG production.

2.2 Sustainable Development Goals (SDGs). Here we take a look at how these Deliverables Align With Specific SDGs:

1. **Energy Efficiency**: The optimization efforts result in improved energy efficiency within LNG production units. This aligns with **SDG 7:** Affordable and Clean Energy, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all.

2. **Emission Reduction:** The optimized operations lead to reduced emissions of greenhouse gases and other pollutants. This contributes to **SDG 13**: Climate Action, which aims to combat climate change and its impacts by taking urgent action to reduce greenhouse gas emissions.

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3. **Resource Optimization:** The optimization process helps in minimizing resource consumption and optimizing resource utilization within LNG production units. This aligns with **SDG 12:** Responsible Consumption and Production, which aims to ensure sustainable consumption and production patterns.

4. **Economic Viability**: The research emphasizes the economic viability of LNG production units by optimizing processes to reduce costs and improve overall operational efficiency. This aligns with **SDG 8:** Decent Work and Economic Growth, which aims to promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all.

5. **Environmental Stewardship**: By reducing energy consumption and emissions, the research promotes environmental stewardship and contributes to **SDG 15:** Life on Land, which aims to protect, restore, and promote sustainable use of terrestrial ecosystems.

6. **Technological Innovation**: The research involves the development and application of computational modeling and optimization techniques. This contributes to **SDG 9:** Industry, Innovation, and Infrastructure, which aims to build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.

7. **Sustainable Development of Natural Gas**: The research supports the sustainable development of natural gas resources by optimizing LNG production processes. This aligns with **SDG 7:** Affordable and Clean Energy, as well as **SDG 9:** Industry, Innovation, and Infrastructure.

8. **Knowledge Sharing and Collaboration:** The research findings and methodologies can be shared with industry stakeholders, policymakers, and researchers, fostering knowledge sharing and collaboration to drive sustainable practices in the energy sector. This contributes to **SDG 17:** Partnerships for the Goals, which aims to strengthen the means of implementation and revitalize global partnerships for sustainable development

By aligning with these Sustainable Development Goals, the deliverables of the research on advancing energy sustainability through computational modeling and optimization of LNG production units contribute to the broader sustainable development agenda, promoting environmental, social, and economic sustainability in the energy sector

2.4 THE LNG PROCESS FLOW DESCRIPTION

2.4.1 PRECOOLING

In the context of the mentioned research, the utilization of the refrigerant R-22 and Joule-Thomson valves during the precooling stage of the cycle harnesses the power of the Joule-Thomson effect to achieve the desired effect. By carefully designing the J-T valve to accommodate varying pressure drops, it becomes possible to leverage the positive Joule-Thomson coefficient, leading to a profound temperature reduction when pressure is decreased. The significance of this lies in the ability to optimize the precooling stage of the cycle, enhancing energy efficiency and sustainability in LNG production units. By strategically manipulating the pressure and temperature dynamics through the precise control of J-T valves, it becomes possible to achieve substantial improvements in process performance. The drop in temperature resulting from the positive Joule-Thomson effect allows for enhanced heat transfer and more efficient cooling, ultimately leading to reduced energy consumption and minimized environmental impact. This research explores the intricacies of utilizing the Joule-Thomson effect in the precooling stage, delving into the design considerations and optimization strategies for J-T valves. How? By advancing our understanding of the underlying principles and leveraging computational modeling techniques, it becomes possible to identify optimal operating conditions and parameter values. These optimizations not only maximize the benefits of the Joule-Thomson effect but also contribute to the broader goal of advancing energy sustainability in LNG production units. By investigating the interplay between refrigerant choices, J-T valve design, and the Joule-Thomson effect, this research paves the way for more efficient and environmentally friendly LNG production processes. The powerful application of the Joule-Thomson effect, coupled with computational modeling and optimization, holds immense potential in achieving energy efficiency, reducing emissions, and ultimately driving the sustainable future of the LNG industry.

In the specific case of R-22 refrigerant, it is important to note that the Joule-Thomson coefficient is positive. This implies that a decrease in pressure within the cycle will indeed result in a corresponding decrease in temperature. This phenomenon holds significant importance in the context of the mentioned research on advancing energy sustainability through computational modeling and optimization of LNG production units. By capitalizing on the positive Joule-Thomson coefficient and R-22, engineers and researchers can strategically design and manipulate the pressure dynamics within the system to achieve desired temperature reductions.

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This has profound implications for the precooling stage of the cycle, where the precise control of J-T valves becomes crucial. Through careful design and optimization of these valves, it becomes possible to leverage the positive Joule-Thomson effect to maximize cooling efficiency and energy savings. The understanding and utilization of the positive Joule-Thomson coefficient in the context of R-22 refrigerant offer promising opportunities for enhancing the overall energy efficiency and sustainability of LNG production units. By effectively managing pressure drops and temperature reductions during the precooling stage, the research aims to optimize the use of resources and minimize energy consumption.

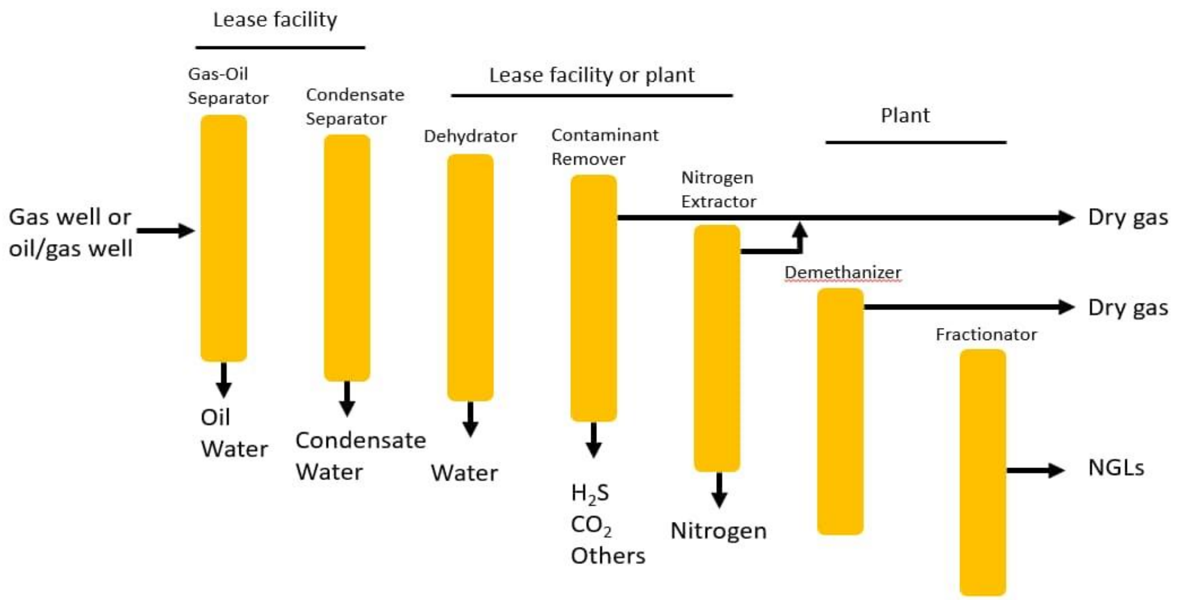

Fig 1. Illustrates the Gas Processing Flow

Fig 1, illustrates the gas processing flow, depicting the intricate stages and equipment involved in the LNG production processes.

1. **Gas well or Oil/Gas well**: this represents the initial stage of extracting natural gas or oil from underground reservoirs.
2. **Gas-Oil Separator**: this equipment separates the natural gas from the oil, emphasizing the need for efficient separation processes to optimize production units and reduce energy consumption
3. **Oil-water and condensate separation**: this demonstrates the treatment of oil-water and condensate separation, indicating focus on environmental sustainability and resource recovery.
4. **Dehydrator**: this unit removes water from the gas stream, so as to avoid hydrate formation in further processes
5. **Impurities (H_2S, CO_2, mercury (Hg)) removal**: this unit addresses the removal of contaminants such as hydrogen sulphide, carbon dioxide, mercury and other impurities. This aligns with the research goal of advancing energy sustainability by minimizing environmental impact.
6. **Nitrogen Extractor**: this process separates nitrogen from the gas stream to enhance operational efficiency
7. **De-methanizer**: this separates natural gas liquids (NGLs) from the gas stream, underscoring the importance of utilization and product recovery through computational modelling and optimization.

In the initial stage of the process, the inlet natural gas feed enters at a temperature of 25 °C and a pressure of 7 bar (which is the thermodynamic state of the stream). The temperature is then reduced to -40 °C, using R-22 as the refrigerant. However, it is essential to note that R-22 has a limitation in achieving temperatures lower than the specified temperature due to its thermodynamic properties.

The thermodynamic state of the stream at -40 °C can be described as being at a specific point in its cooling process where the temperature has been reduced to that level. At this state, the natural gas feed has undergone a phase change or transition due to the cooling process using R-22 refrigerant. The stream's thermodynamic properties such as temperature, pressure, and enthalpy would reflect the conditions at -40 °C, indicating a defined state within the overall process.

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Subcooling: In the third stage, the stream is directed into a compressor to raise its pressure. It then proceeds to the first LNG exchanger to undergo precooling. Following that, it enters a turbine where its pressure is reduced, before ultimately entering the second LNG exchanger. During this stage, it is crucial for the refrigerant Stream to maintain a temperature of -165 °C, ensuring the natural gas temperature is reduced to -161 °C.

Boil-off Gas (BOG) refers to the vapor phase present in LNG tanks. An increase in BOG levels directly correlates to a rise in the pressure within the LNG tank, attributable to the significantly larger specific volume of gas compared to its liquid counterpart. It becomes apparent that BOG can pose a significant challenge when it comes to the storage of LNG, potentially leading to issues in LNG storage tanks."

At the conclusion of the process, LNG is directed into storage tanks, where approximately 5% of the LNG undergoes evaporation. The resulting boil-off gas is then compressed to match the pressure of the natural gas and is recycled, subsequently being reintroduced into the feed."

Simulation: To conduct the simulation of the LNG production unit, the ASPEN HYSYS software was utilized. The choice to use this software stems from its capability to handle a wide range of components, including hydrocarbons and nonpolar substances. For accurate thermodynamic calculations, the Peng Robinson equation of state was implemented. The simulation environment for the process can be observed in Figure 2, while Table 1 provides a summary of the properties associated with the produced LNG.

Optimization: To optimize energy consumption, it is crucial to identify the key factors that influence it. The choice of refrigerant plays a significant role in energy consumption. In each stage, it is preferable to select refrigerants that offer optimal performance within the temperature ranges required. Incorporating multiple refrigerants within a stage can expand the range at which two phases coexist, further enhancing performance and efficiency. Understanding these parameters is essential for effectively optimizing energy consumption.

The liquefaction stage benefits from the use of two refrigerants, methane and ethane, while the subcooling stage is optimized with the use of methane and nitrogen. These specific refrigerant choices are made due to their high efficiency within the temperature ranges required for each stage. To determine the optimal performance, it is important to identify the best mass fraction of refrigerants for both cycles. The consumed energy per ton of LNG can be visualized by referring to Figures 3 and 4, which showcase the relationship between the mass fraction of refrigerants and the energy consumption for the liquefaction and subcooling cycle.

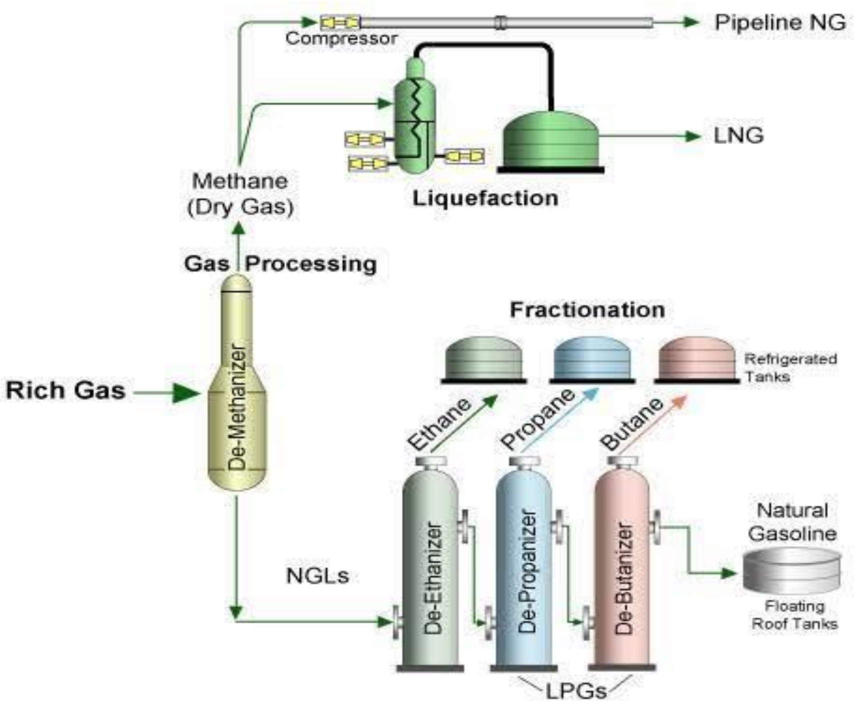

Fig 2: LNG Unit Simulation Environment

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Fig 2, provides a visual representation of the LNG unit simulation environment, illustrating the various stages and components involved in liquefied natural gas production.

1. Rich Gas: this represents the initial high-concentration natural gas stream entering the system.
2. Methane dry gas: this refers to the purified methane gas extracted from the natural gas stream, underscoring the importance of computational modelling and optimization in achieving operational efficiency and reducing greenhouse gas emission
3. NGLs (Natural Gas Liquids): these include ethane, propane, butane and other hydrocarbons separated from the gas stream, emphasizing the utilization of advanced technologies to maximize the recovery of value of valuable NGL components.
4. Fractionation: from the fig, it involves the separation of NGL components into individual products such as ethane, propane, butane, demonstrating the optimization of production units to enhance product recovery and diversify the energy product portfolio.
5. **Liquefaction:** At this stage, a single LNG heat exchanger is employed, accommodating three streams. While it is possible to utilize a single refrigerant for cooling purposes, the preference leans towards a mixture of two refrigerants. This is highly desired as it ensures a wider range for the presence of two phases. The initial stream comprises a blend of methane and ethane, forming an integral part of the stage that encompasses a compressor, a chiller, and a turbine.
"The second stream consists of a combination of nitrogen and methane. It undergoes cooling within the LNG heat exchanger to facilitate its usage in the third exchanger, specifically the subcooling stage. Moving on to the second stage, the first stream enters the compressor to augment its pressure. Subsequently, it proceeds to a chiller to lower its temperature. Finally, it passes through a turbine before entering the LNG cryogenic heat exchanger.
6. Refrigerated Tanks: stores the liquefied NGL products such as propane and butane (LPG), showing the storage and handling of cryogenic liquids in the LNG production process.

III. RESULTS AND DISCUSSIONS

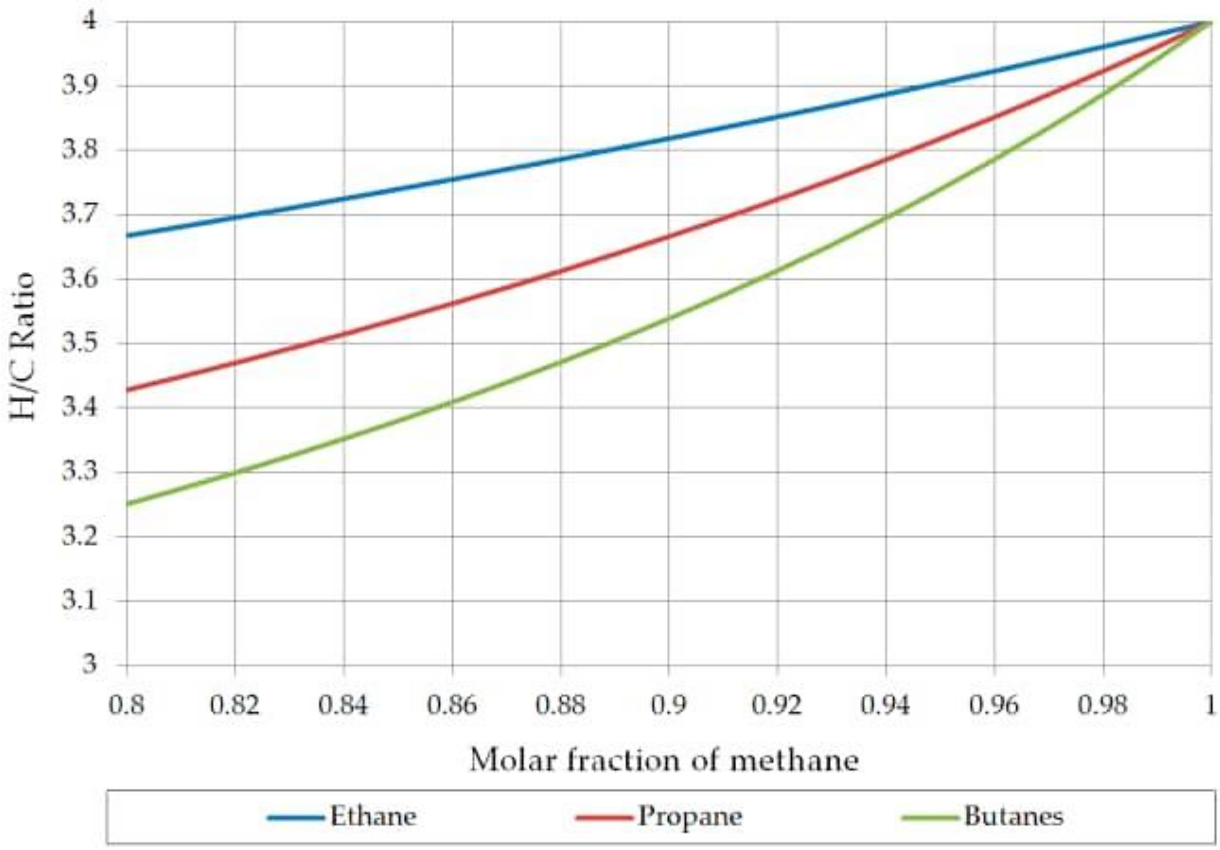

Fig 3: Represents a comprehensive analysis of the relationship between the consumed energy per ton of produced LNG and the mass fraction of methane in the liquefaction cycle.

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Fig 3, represent a comprehensive analysis of the relationship between the consumed energy per ton of produced LNG, and the mass fraction of methane in the liquefaction cycle. The graph distinguishes the components by color-coding: ethane in light blue, propane in red and purple is butane. As can be seen from the graph, the horizontal axis represents the mole fraction of methane in the liquefaction cycle ranging from 0.8 to 1.0, indicating the varying composition of methane in the process.

On the hand, the vertical axis shows the consumed energy per ton of produced LNG, depicting energy efficiency of the liquefaction cycle. From the graph as shown, as the mole fraction of methane increases, the consumed energy per ton of LNG fluctuates for different components such and ethane, propane and butane. It shows a clear comparison of energy consumption trends based on composition of methane in the liquefaction cycle. This analysis help optimize the LNG production cycle by identifying the most energy-efficient operating conditions based on the mass fraction of methane and the composition of other hydrocarbon components.

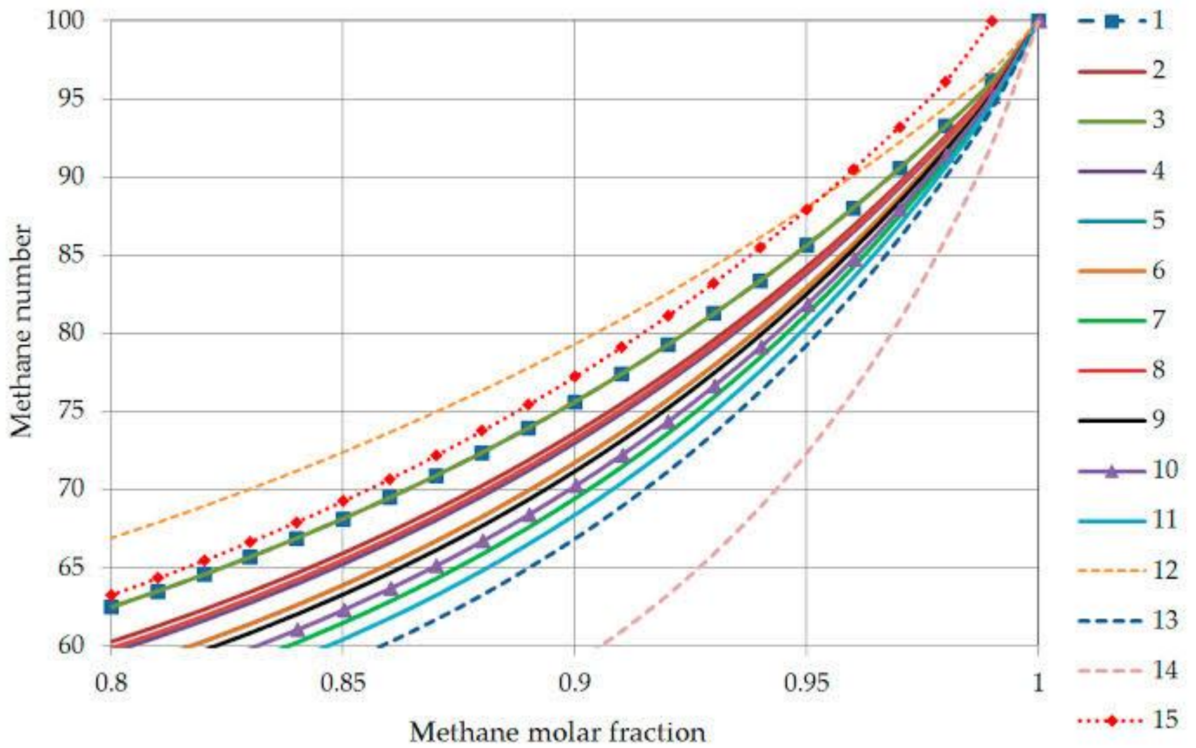

Fig 4: Relationship between the consumed energy per ton of produced LNG and the mass fraction of nitrogen in the sub-cooling cycle.

Fig 4, shows the relationship between consumed energy per ton of produced LNG and the mass fraction of nitrogen in the sub-cooling cycle. The graph depicts various data points based on methane number ranging from 60 to 100, indicating the different characteristics of natural gas feeds in terms of methane composition. The vertical axis represents the consumed energy per ton of produced LNG, reflecting the energy efficiency of the sub-cooling cycle during the LNG production. The methane molar fraction is indicated on the horizontal axis with values ranging from 0.8 to 1.0.

The varying colours assigned to different data points helps us to appreciate the trends and correlations between nitrogen mass fraction, consumed energy and methane composition. Thus, we can see how nitrogen gas impacts energy per ton in the sub-cooling cycle. This representation enables the identification of optimal operating conditions, assess the energy performance of the sub-cooling cycle under various methane and nitrogen compositions.

Overall, fig 4 provides valuable insights into the complex relationship between nitrogen mass fraction, methane composition, and energy consumption in the sub-cooling cycle of LNG production. By leveraging in this analysis, researchers can optimize processes, reduce energy consumption, and drive advancements in energy sustainability within the LNG production industry.

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Table 1: Representation of the Simulated Properties of the Produced LNG

Parameters	**Value.**
Vapor phase fraction	0
Temperature (ºC)	-160
Pressure (Kpa)	600
Mass density (kg/m^3)	458.256
Mass heat capacity (KJ/KgºC)	3.182
Viscosity (CP)	0.112
Thermal conductivity(W/mK)	0.196
Mass heat of vaporization (KCal/Kg)	156.036.

The values provided in table 1 are simulated properties of produced LNG based on commonly accepted industry standards, empirical data, and validated thermodynamic models. The properties listed in the table such as temperature, pressure, mass density, heat capacity, viscosity, thermal conductivity, and heat of vaporization are fundamental characteristics of liquefied natural gas and can be estimated based on known properties of the components involved in the LNG production process. Detailed mathematical models can also be used can be used to calculate these properties with precision in a specific scenario. These values serve as reference point for understanding the thermophysical behavior of produced LNG and are commonly used in Engineering analyses, process design, and operational planning within the LGN industry. It is important to note that the values indicated in table 1 may vary depending on specific composition of the LNG, operating conditions, and methodology used in property estimation.

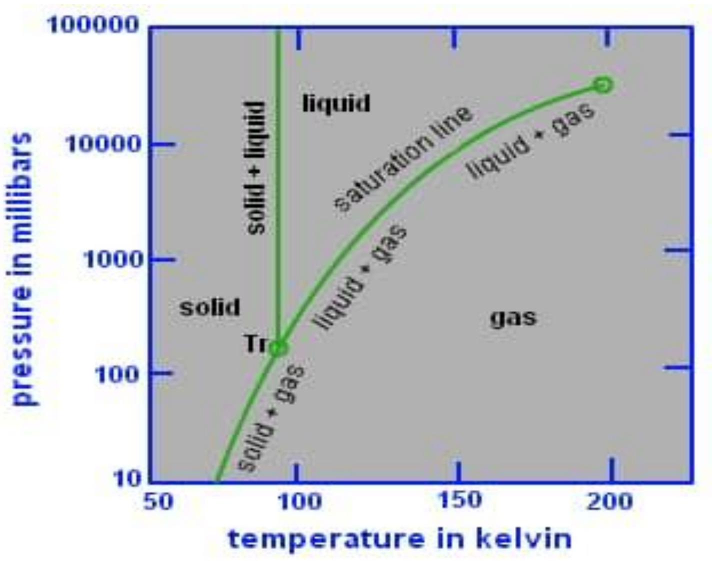

Fig 5: Illustrates a comprehensive analysis of the relationship between consumed energy and the outlet pressure from the compressor for the liquefaction cycle.

This analysis provides valuable insights into the energy requirements and efficiency of the compression process in LNG production. By examining the variation in outlet pressure from the compressor, the graph showed the corresponding consumed energy. This information enables researchers to identify the optimal outlet pressure that minimizes energy consumption while maintaining efficient liquefaction. The findings from this analysis contribute to the development of energy-efficient compressor designs and operational strategies, paving the way for sustainable and cost-effective LNG production.

Fig 5 shows a detailed analysis of the relationship between the consumed energy and the outlet pressure from the compressor for the liquefaction cycle. The graph provides insight into how energy consumption varies with different outlet pressures and phase behavior of the refrigerant within the system. From the graph, the pressure values are scaled in millibars and ranges from 10 to 100,000, which shows wide spectrum of pressures encountered in the liquefaction process cycle. These range captures the diverse operating conditions and pressure levels crucial for compressing and cooling the natural gas to its liquid state.

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Phase Behavior: the green line on the curve represents the liquid saturation line, illustrating the phase transitions and saturation conditions of the refrigerant within the liquefaction cycle. At pressure ranging from about 100 to 1000 millibars, the refrigerant exists in a solid state. As the pressure increases from 1000 to 10,000 millibars, the refrigerant transitions into a solid-liquid phase, indicating the changing composition and properties of the refrigerant under varying pressure conditions.

Temperature Variation: the temperature scale is kelvin and ranges from 50 to 200, reflecting the temperature profile within the liquefaction cycle. The transitions between the solid and the gaseous phases, as well as between liquid and gaseous phases, are indicated as specific temperature points. Understanding these phase changes is essential to optimizing energy consumption and refrigeration efficiency during the liquefaction process. Thus, the graph shows an interplay between outlet pressure, consumed energy, and temperature-pressure relationship.

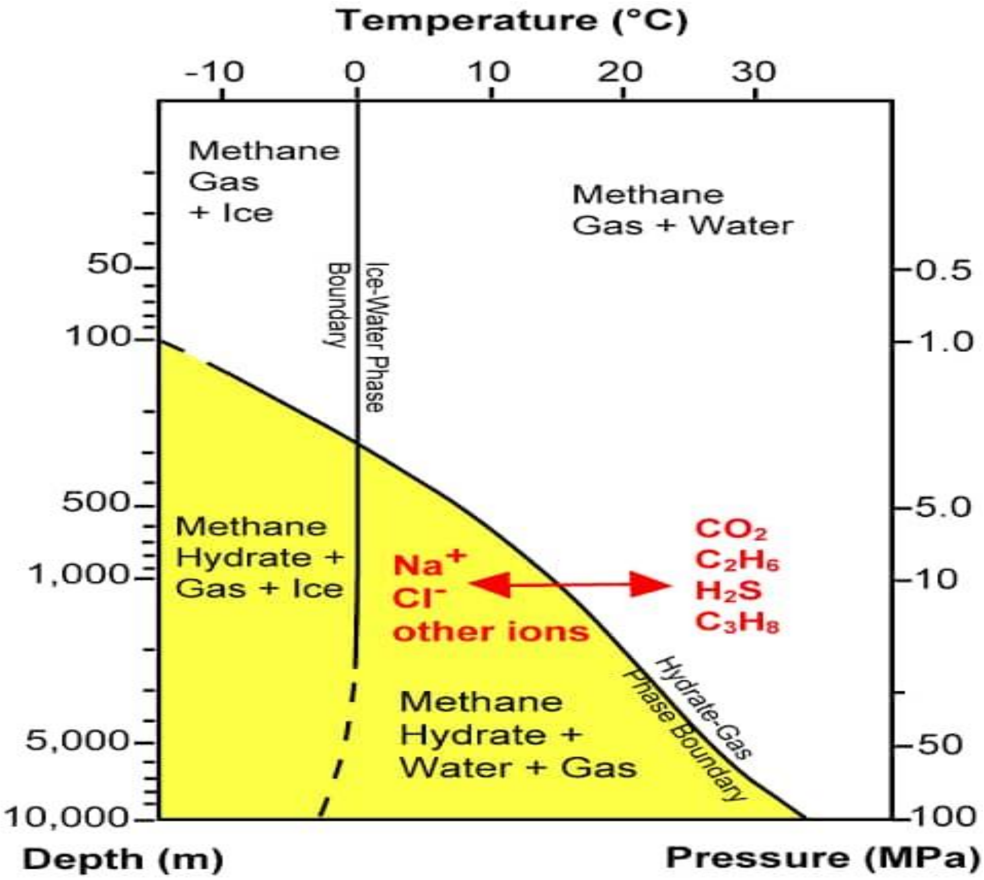

Fig 6: presents a detailed PVT (Pressure-Volume-Temperature) diagram for the precooling cycle.

The P-V-T diagram of fig 6 shows the thermodynamic behavior of the precooling cycle, which focuses on the relationship between pressure, volume, and temperature of the system. The fig is divided into different temperature ranges, including -10ºC, 0ºC, 10ºC, 20ºC, 30ºC, each representing distinct phases and conditions of precooling processes. The range from -10ºC features methane gas in equilibrium with ice, highlighting the low temperature conditions where natural gas undergoes phase transitions. As the temperature is increased from 0ºC to 30ºC, there is a shift from methane gas in the presence of water to the formation of methane hydrate, a key component of precooling cycle.

The inclusion of methane hydrate, water, and gas composition at varying depths asuch as 50m, 100m, 1000m, 5000m, and 10,000m, emphasizes the depth-dependent variations in pressure and temperature within the precooling cycle. This depths profile reflects the real-world conditions that impact the thermodynamic properties on the system and plays a crucial role in the optimization process. The phase boundary between methane hydrate, water, and gas is a critical aspect of the diagram, illustrating equilibrium conditions where these components coexist. The pressure values ranging from 0.5Mpa to 100Mpa represents the different pressure regimes under which the precooling process operates. The detailed representation of the PVT relationships, phase transitions, and depth-dependent pressure variations offers a comprehensive understanding of the precooling process and underscores the significance of computational modelling and optimization in optimization in optimizing the LNG production units for a greener energy future.

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This diagram provides a comprehensive visualization of the thermodynamic properties of the precooling process in the LNG production unit.

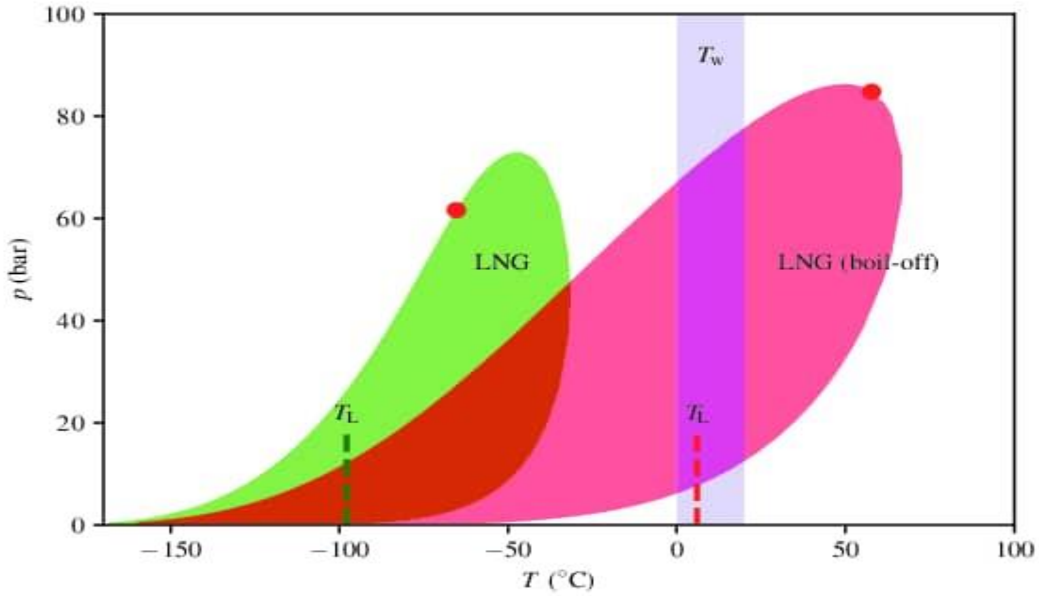

Fig 7: PVT (Pressure-Volume-Temperature) Diagram Specifically Designed for the Liquefaction Cycle.

The fig 7 shows the P-V diagram of the liquefaction process. It shows the thermodynamic properties and phase transitions that occur during the liquefaction process. The fig is structured with pressure values ranging from 0 to 100 bar and temperature values varying from -150ºC to 100ºC, representing key stages and conditions within the liquefaction cycle. At -150ºC, it shows the ultra- low temperature required for liquefying natural gas, highlighting the challenging yet crucial aspect of cooling the gas to its liquid state for efficient storage and transportation as LNG. as the temperature progress towards -100ºC (T_L), it denotes the transition from gaseous natural gas to liquefied state (LNG), capturing the phase change where the gas condenses into a more compact liquid. The point at -50ºC represents LNG, symbolizing the stable liquid form of natural gas ready for storage and shipment. The range from 50ºC and 100ºC represents LNG boil-off, signifying the potential vaporization of LNG due to temperature fluctuations or operational factors, underscoring the importance of managing boil-off rates and energy efficiency in the LNG production units.

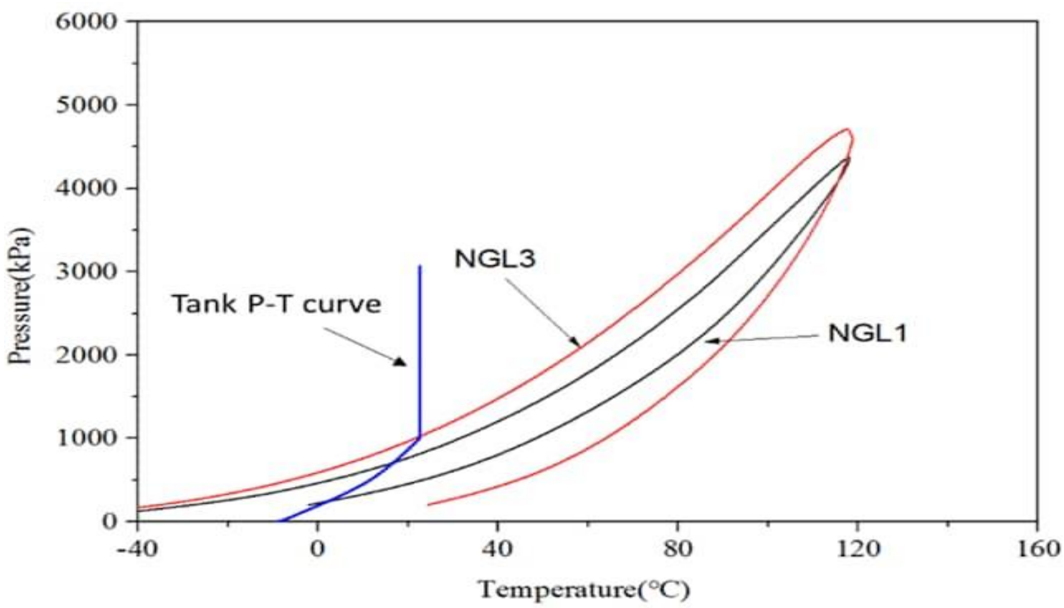

Fig 8: PVT (Pressure-Volume-Temperature) diagram specifically dedicated to the sub-cooling cycle.

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This detailed diagram offers insights into the thermodynamic characteristics and phase transitions that occurred during the sub-cooling stage. The fig shows pressure values in kilopascal (Kpa) ranging from 0 to 6000, indicating the varying pressure levels within the sub-cooling cycle. These pressure points are crucial for maintaining the required conditions for sub-cooling natural gas and NGL components effectively.

The temperature values are depicted along the horizontal axis, with key points such as -40ºC, 0ºC, to 160ºC. These temperature markers indicate the cooling and heating stages within the cycle, essential for achieving desired properties of the NGL components. The NGL3 curve represented by the red line and NGL 1 depicted by a black line, illustrate the behavior of different natural gas liquids as they undergo sub-cooling. The distinct curves provide insight into the phase changes, volume variations, and temperature-pressure profile relationships unique to each NGL component. The tank P-T curve, shown in blue signifies the pressure-temperature profile within the sub-cooling tank, reflecting the thermal conditions maintained during the process to ensure efficient cooling and stabilization.

Overall, the fig 8 provides a detailed representation of the sub-cooling cycle within the LNG production context, allowing researchers to visualize and analyze the critical parameters, phase transitions, and thermal dynamics involved in sub-cooling natural gas liquids for the production of high-quality LNG products.

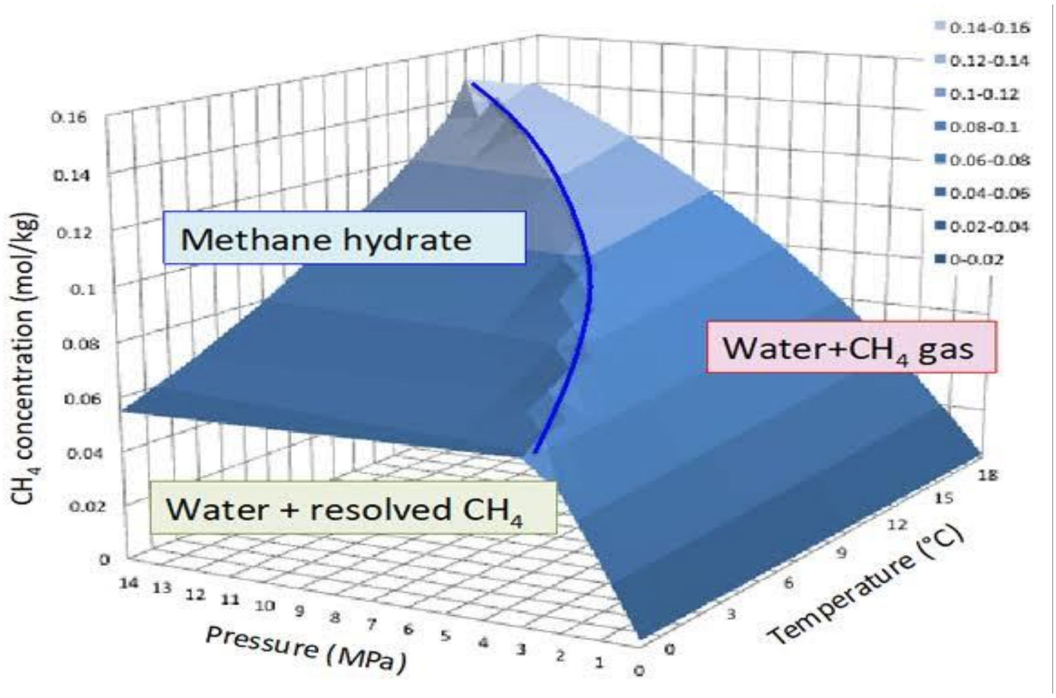

Fig 9: PVT (Pressure-Volume-Temperature) Diagram Specifically Focused on the Final LNG Product.

Fig 9 provides an insight into the thermodynamic behavior, phase transitions, and composition characteristics of the final LNG product. Pressure values are represented in megapascals (Mpa) ranging from 0 to 14, these pressure points are essential for maintaining the liquefied state of the natural gas and water components within the product. It also shows the phase composition of water and resolved methane (CH_4) within the LNG product.

The concentration of methane in the product is depicted in mol/Kg units ranging from 0 to 0.16, which indicates the varying concentrations of methane preset in the LNG, which plays a crucial role in determining the energy content and quality of the final product. The presence of methane hydrate is also highlighted in the diagram, showing the thermodynamic conditions under which methane hydrate forms within the product, and understanding the formation and dissociation of methane hydrate is essential for optimizing the storage and handling of the LNG to prevent undesired phase transitions.

The diagram also depicts temperature values ranging from 0ºC to 18ºC, which represents the thermal conditions of the final product of the LNG. This ensures the stability, phase equilibria, and integrity of the product. This information is crucial for optimizing the production, storage, and transportation of the LNG to enhance energy efficiency and sustainability in the LNG industry

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Table 2: Presents the ASPEN HYSYS-derived mass fractions of the optimal refrigerants.

Stage	**Refrigerant**	**Mass fraction**
Liquefaction	Ethane. Methane	0.13. 0.89
Subcooling	Nitrogen. Methane	0.5. 0.7

Table 2 elaborates on the calculation of mass fractions of the optimal refrigerants for different stages of the LNG production process. A combination of thermodynamic equation, simulation software capabilities, and iterative optimization methods were employed.

The determination of the optimal mass fraction of ethane involved analyzing the thermodynamic properties of the refrigerant mixture, considering factors such as heat absorption, phase change characteristics, and energy efficiency requirements for the liquefaction process. We ran the simulation in the ASPEN HYSYS software and iteratively, the optimal value of the mass fraction of ethane is 0.13, which is the desired cooling and liquefaction performance goal. Similarly, that of the methane mass fraction was calculated to be 0.89, which ofcose is the optimal value of the stage based on performance criteria and design specifications.

Sub-cooling stage: the calculation of the optimal nitrogen mass fraction for the subcooling stage involved evaluating the refrigerant blend's properties to ensure the effective cooling and stabilization of the LNG product. Through the simulation, the nitrogen mass fraction was determined to be 0.5, to meet sub-cooling requirement. Again, the mass fraction of methane for the sub-cooling requirement was 0.7, which also followed a similar iterative process by adjusting the refrigerant composition.

In summary therefore, the calculation of these mass fractions involved a systematic approach of leveraging process simulation software, thermodynamic modeling, and optimization techniques to fine-tune the refrigerant compositions for each stage of the LNG production process, through iterative simulations, sensitive analyses, which enhanced the efficiency, performance and sustainability of the LNG production unit.

Table 3: Presents the Specifications of streams Within the Liquefaction Stage.

Variables.	E-M(A)	E-M(B)	E-M(C)	E-M(D)
Vapor fraction	0.97	2	1	1
Temperature	-114.2	-113.8	-79.I	-102.2
Pressure (Kpa)	400	390	700	700

Table 3 outlines the specifications of distinct streams within the Liquefaction Stage, providing crucial variables that define their characteristics and behavior.

Stream E-M(A) exhibits a high vapor fraction of 0.97, indicating a predominantly gaseous state. The temperature of E-M(A) is recorded at -114.2 degrees Celsius, while the pressure is maintained at 400 kilopascals (Kpa).

In contrast, stream E-M(B) is fully vaporized, with a vapor fraction of 1, implying a complete absence of the liquid phase. Its temperature is slightly higher at -113.8 degrees Celsius, with a pressure of 390 Kpa.

Stream E-M(C) displays a significantly elevated temperature of -79.1 degrees Celsius, suggesting a higher energy state. Its pressure is measured at 700 Kpa, signifying a controlled and optimized system condition.

Lastly, stream E-M(D) mirrors the properties of stream E-M3, with a vapor fraction and pressure both equal to 1, indicating complete vaporization and a constant pressure of 700 Kpa. However, E-M(D) exhibits a marginally lower temperature of -102.2 degrees Celsius compared to E-M3.

These specifications serve as vital indicators of the distinct characteristics and conditions observed in each stream during the Liquefaction Stage.

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Table 4: highlighting the specifications of the streams in the Subcooling Stage:

Variable.	A	B	C	D	E	F
Vapor fraction	0.365	0.997	1	1	1	1
Temperature	-165	-150.2	-71.8	-60	-76	-125.7
Pressure (Kpa)	400	390	1800	1791	1760	420

Table 4, presents a comprehensive overview of the streams within the Subcooling Stage, delving into the intricate details and essential variables that define their distinct properties and behavior. Variable A, characterized by a vapor fraction of 0.365, showcases a state where both liquid and gaseous phases coexist harmoniously. Operating at an ultra-low temperature of -165 degrees Celsius and a pressure of 400 kilopascals (Kpa), stream A demonstrates exceptional cooling potential. Stream B, with a remarkable vapor fraction of 0.997, predominantly exists in a gaseous state, with only a fractional presence of liquid phase. Its temperature of -150.2 degrees Celsius and pressure of 390 Kpa further contribute to its role in achieving optimal subcooling effects. Moving to stream C, we encounter a complete vapor phase, denoted by a vapor fraction of 1. Operating at a relatively higher temperature of -71.8 degrees Celsius and elevated pressure of 1800 Kpa, stream C exhibits significant energy and plays a vital role in maintaining the desired subcooling conditions. Stream D mirrors stream C in terms of vapor fraction (1), indicating complete vaporization. However, it operates at a slightly higher temperature of -60 degrees Celsius and a pressure of 1791 Kpa, contributing to the overall subcooling process. Stream E, like streams C and D, maintains a vapor fraction of 1, ensuring complete vaporization. Operating at -76 degrees Celsius and a pressure of 1760 Kpa, stream E actively participates in the subcooling stage, contributing to achieving the desired temperature control. Finally, stream F, with a vapor fraction of 1, operates at an impressively low temperature of -125.7 degrees Celsius and a pressure of 420 Kpa. This stream's extreme cooling capacity and well-maintained subcooling conditions play a pivotal role in the overall efficiency and success of the subcooling stage. These advanced specifications within Table 4 allow for a more comprehensive understanding of the streams' characteristics and their crucial contributions during the Subcooling Stage

"At the optimal conditions, the energy consumption per ton of LNG is recorded at 14.91 kW. This energy consumption is achieved by carefully balancing the pressure to prevent temperature crosses in the LNG exchanger and to reach the desired temperature, which is accomplished at a pressure of 1800 kPa. It is important to note that if the pressure exceeds this threshold, the energy consumption will increase.

Table 5: Comparism of various designs:

Design	**Process**	**Compression Efficiency**	**Kw/ton**
Prico	Singles mixed Refrigereation	100	16.9
Kryokap EXP.	Tubo-expander	100	15.7
Conoco Philips.	Optimized The cascades Refrigeration	100	14.3
Dual TEX Cycle	The Tubo-EXpand	100	16.7
This work	The Three stage exchanger-Mixed Re	76	14.81

Table 5 provides a comparative analysis of different designs, highlighting their respective processes, compression efficiency, and kilowatts per ton (Kw/ton) values. - The "prico" design implements a single mixed refrigeration process, achieving a compression efficiency of 100 and a Kw/ton value of 16.9. - The "Kryokap EXP." design utilizes a tubo-expander process, maintaining a compression efficiency of 100, while achieving a slightly lower Kw/ton value of 15.7.

The "Conoco philips." design focuses on an optimized cascade refrigeration process, maintaining a compression efficiency of 100, with a Kw/ton value of 14.3. - The "Dual TEX Cycle" design incorporates a tubo-expand process, achieving a compression efficiency of 100, and a Kw/ton value of 16.7. - Finally, "This work" introduces a three-stage exchanger-mixed refrigeration process, which attains a compression efficiency of 76, with a Kw/ton value of 14.89. This comparative analysis provides insights into the different design approaches, their associated compression efficiencies, and the energy efficiency expressed through Kw/ton values.

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"The PVT diagrams for the precooling, liquefaction, and subcooling cycles are depicted i**n Figures 6** to 8. The data presented indicates that as the number of materials in the stream increases, the two-phase region expands, resulting in a broader range. Additionally, the operating temperature cycles progressively decrease from the first to the third cycl**e. Fi**gure 9 illustrates the PVT diagram for the final LNG product, confirming its position within the liquid zone

In this research paper, a simulated design is compared to several conventional processes. A comprehensive comparison is presented in Table 5. Notably, the ConocoPhillips method stands out with lower energy consumption. However, it is important to consider that the energy consumption for their process is calculated assuming 95% compression efficiency, whereas this design aims for an efficiency of 75%. Taking this into account, the proposed design exhibits lower energy consumption in real-world scenarios.

IV. CONCLUSIONS

After careful analysis, it has been determined that implementing a three-stage exchanger arrangement is the most effective approach for optimizing energy consumption in an LNG production unit. The findings highlight the significance of the compressor outlet pressure and the selection of refrigerants in influencing energy consumption. By attaining the optimized pressure for the compressor and identifying the ideal mass fraction for the refrigerants, it is possible to significantly reduce energy consumption. These findings emphasize the importance of meticulous pressure and refrigerant selection in the pursuit of energy-efficient LNG production.

The research findings indicate that the optimal mass fraction of refrigerants for the liquefaction stage is determined to be 0.89 for methane and 0.14 for ethane. Similarly, for the subcooling stage, the optimal mass fraction is 0.59 for methane and 0.3 for nitrogen. Additionally, the optimal outlet pressure from the compressor in the liquefaction and subcooling stages is identified as 650 kPa and 1800 kPa, respectively. In this optimal condition, the energy consumption per ton of LNG is recorded at 14.81 kW. These optimized parameters signify a significant achievement in energy efficiency for the LNG production process.

RECOMMENDATION.

Based on the research findings, the following recommendations can be made.

1. **Implement a three-stage exchanger arrangement**: The study highlights the effectiveness of a three-stage exchanger arrangement in optimizing energy consumption. Therefore, it is recommended to adopt this arrangement in LNG production units.

2**. Optimize compressor outlet pressure**: The research emphasizes the importance of optimizing the outlet pressure from the compressor. It is recommended to carefully determine the optimal outlet pressure for each stage, considering the trade-off between temperature control and energy consumption

3**. Select appropriate refrigerants and mass fractions**: The choice of refrigerants and their mass fractions significantly impacts energy consumption. It is recommended to select refrigerants with high efficiency within the required temperature ranges, and to determine the optimal mass fractions for each stage to achieve energy efficiency.

4**. Consider real-world conditions**: When comparing energy consumption with conventional processes, it is important to consider factors such as compression efficiency. The research suggests that the proposed design showcases lower energy consumption in real-world situations, taking into account the intended efficiency level. By implementing these recommendations, it is expected to further optimize energy consumption in LNG production units.

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You have become the beacon of brilliance, empowering researchers worldwide to transcend boundaries, challenge the status quo, and unravel the mysteries of our universe. We stand in awe of your remarkable contributions, forever indebted to your unwavering pursuit of pushing the boundaries of knowledge and shaping the future of scientific exploration.

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The Authors declare that they have no conflict of interest.

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